Magnetic Amplifiers and Ferromagnetic Core Phenomena

I. General

The non-linear λ-i characteristics of various types of ferromagnetic core materials makes possible a wide variety of useful applications, some of which are discussed below.

II. Inductance

It is well to begin with a look at inductance. One possible definition of inductance which is applicable in most cases is

$$L = \frac{\lambda}{i} = \frac{N\phi}{i} \qquad (1)$$

Based on this definition, L is constant when the λ-i curve is a straight line, as in figure 1:

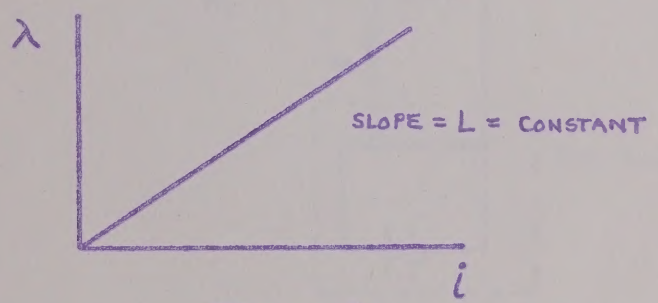


Figure 1

However, we begin to have difficulty defining L when we consider a non-linear λ-i curve as in figure 2, since L is not now a constant, but varies with the degree of saturation.

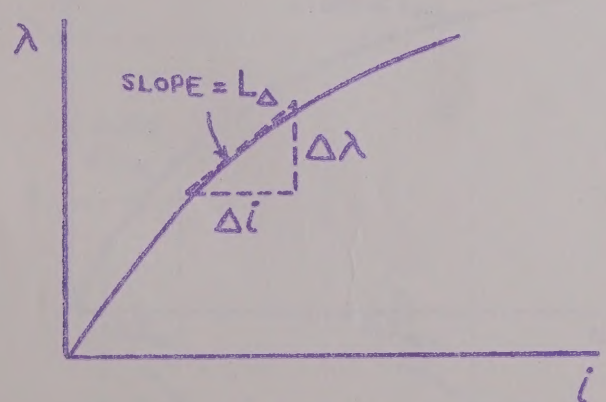


Figure 2

The method which is sometimes used for such cases is to define an incremental inductance, L_Δ, which will be approximately constant over a small range of i by

$$L_\Delta = \frac{\Delta\lambda}{\Delta i} = \frac{N\Delta\phi}{\Delta i} \qquad (2)$$

Note that this incremental inductance decreases as the degree of saturation increases.

III. Variable Inductance Circuit

Consider the circuit arrangement of figure 3:

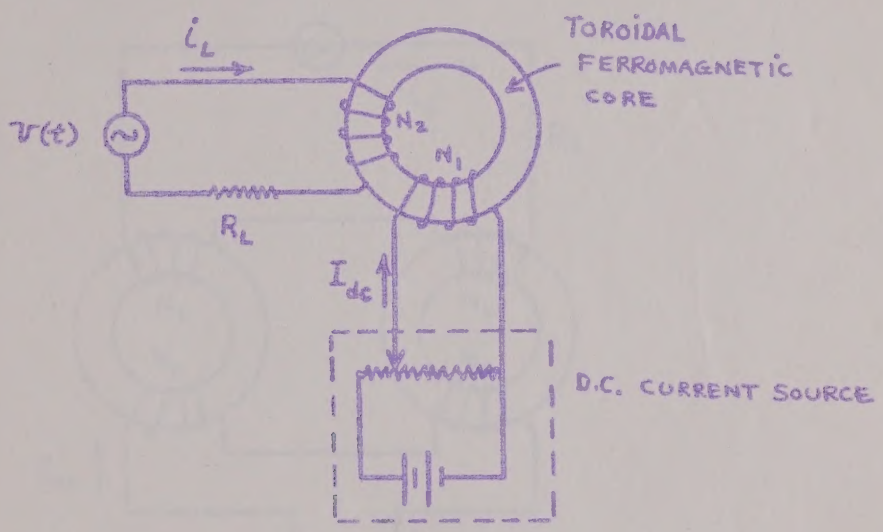


Figure 3

We will assume a no-hysteresis saturation characteristic for the core material such as

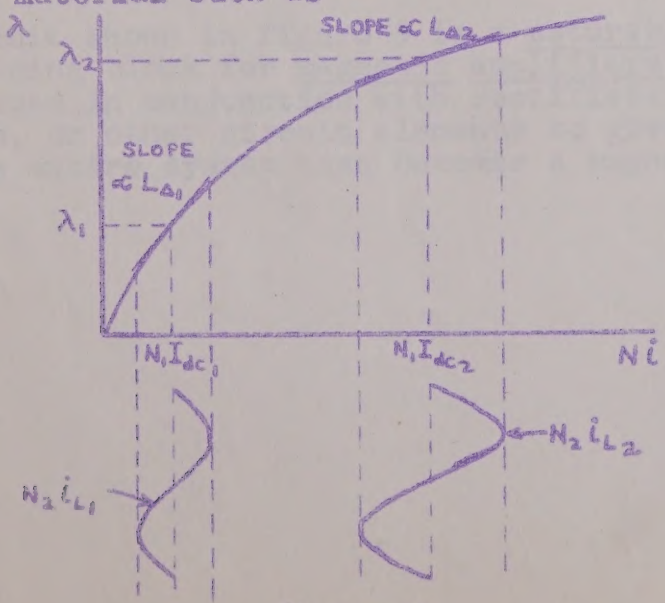


Figure 4

The first case corresponds to a control winding current of value I_{dc_1}, giving a core bias of λ_1. The AC current will then cause variations in λ about this value, resulting in an effective inductance $L_{\Delta 1}$. When the control current is increased to I_{dc_2}, the effective inductance is $L_{\Delta 2}$ which is less than $L_{\Delta 1}$, giving a greater AC load current. If the number of turns on the windings are properly chosen, a small change in control current, I_{dc}, can give a relatively large change in the AC load current.

With the arrangement of figure 3, it is necessary to specify a constant current for the D.C. control winding so that the induced voltage due to the alternating component of core flux does not change the control current. The ill effects of induced voltages in the control winding are overcome by using either a three-legged core, or two separate cores as in figure 5:

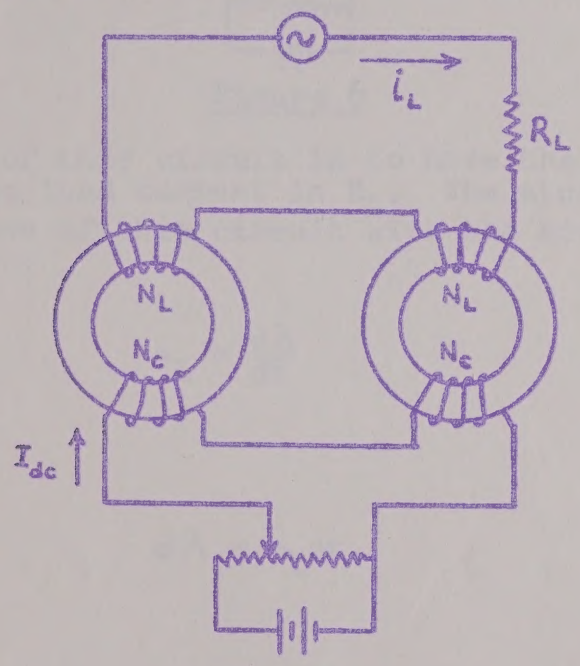
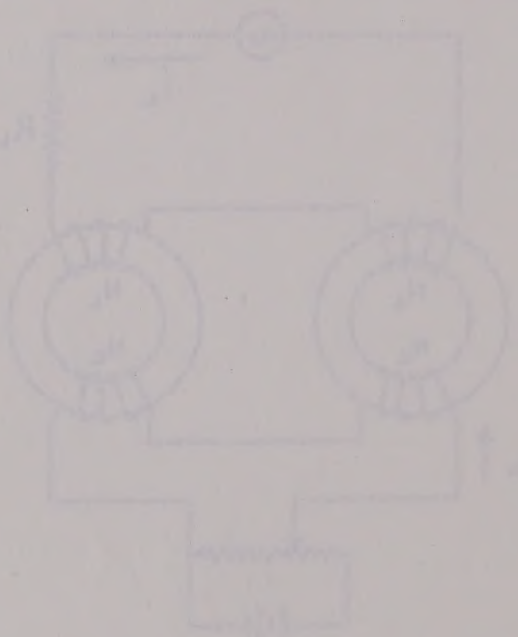


Figure 5

The circuit shown in figure 5 is a saturable reactor. It is a basic building block for magnetic amplifiers. When the saturable reactor is used in conjunction with rectifiers, resistors, transformers, or other circuit elements to give amplification or control, the entire system then becomes a magnetic amplifier.



IV. A Simple Magnetic Amplifier

A basic magnetic amplifier is given in figure 6, where the coils represent the windings in figure 5.

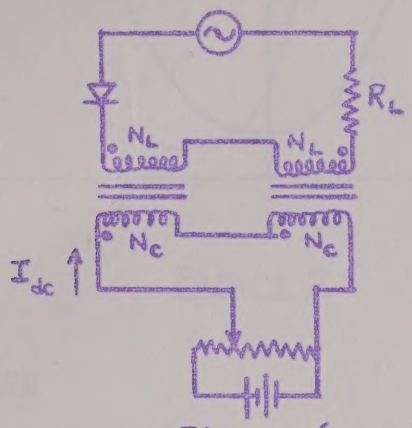


Figure 6

The action of this circuit is to have the control current, I_{dc}, control the load current in R_L. The student should reason out the operation of this circuit with the aid of a second form of Faraday's Law;

$$e_L = \frac{d\lambda}{dt} \tag{2}$$

from which

$$d\lambda = e_L dt$$

or

$$\lambda = \int e_L dt + \lambda_o \tag{3}$$

Important characteristics of magnetic amplifiers are gain, response time, bandwidth, etc., which can generally be improved using various feedback techniques. For instance a typical load current versus control current characteristic is given in figure 7, with and without feedback.

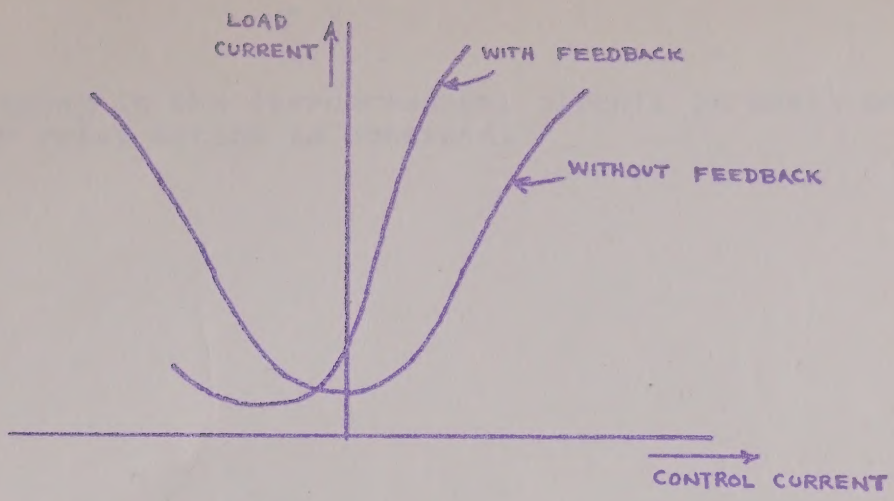


Figure 7

V. Ferro-Resonance

Another application of the saturable reactor is in the ferro resonant circuit of figure 8. A resonant circuit containing an iron-core reactor possesses a sharply discontinous current-voltage characteristic. This depends on the fact that the current in a tuned circuit varies sharply with inductance near the resonant frequency.

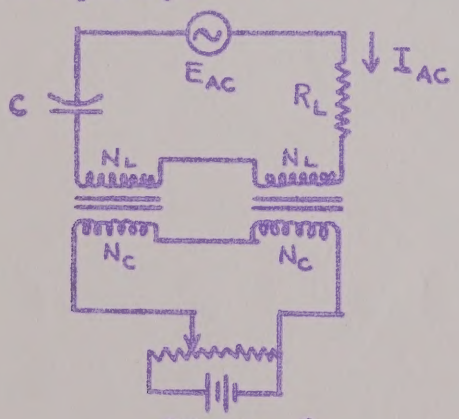


Figure 8

The characteristics of this circuit are:

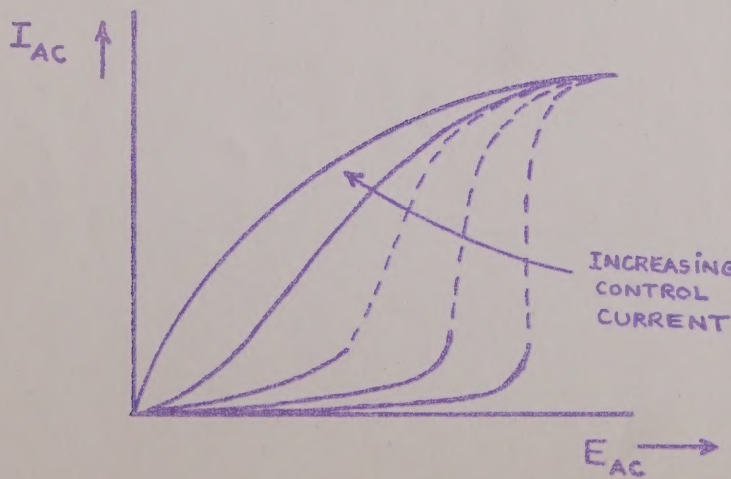
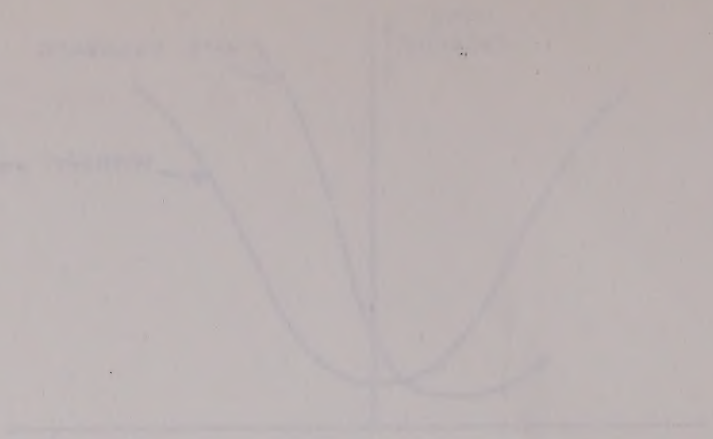


Figure 9



If the damping in the ferro-resonant circuit is small enough, instability or relay action is obtained.

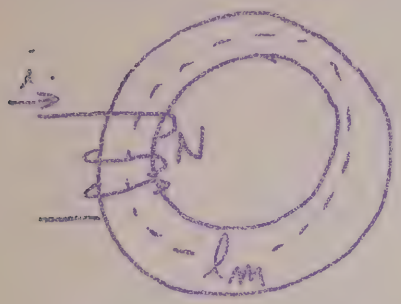
$$\frac{V_1}{R_0} - \frac{V_2}{R_0} = \frac{V_L}{Z_L} = \frac{V_1 + V_2}{Z_L}$$

$$Z_L = R_0 \left(\frac{V_1 + V_2}{V_1 - V_2} \right)$$

$$= R_0 \left\{ \frac{1 + K_L}{1 - K_L} \right\}$$

SUMMARY OF FERROMAGNETIC MATERIALS AND DEVICES

1. THE B-H LOOP



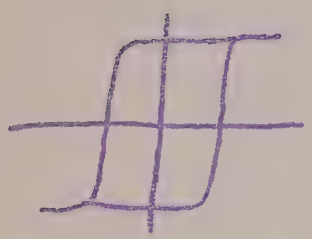
$$B = \frac{\phi}{A}$$

$$H = \frac{Ni}{l_m} = \frac{Ni}{2\pi r_m}$$

(AMPS/M) (AMPS) (METERS)

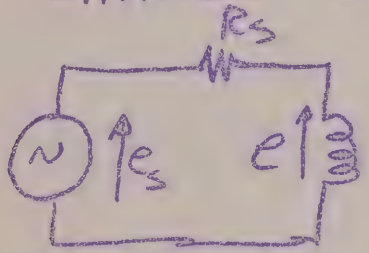
$$H = \frac{0.4\pi Ni}{2\pi r_m}$$

(OERSTED) (AMPS) (CM)



μ AND L OF LITTLE USE WITH SATURATING CORES.

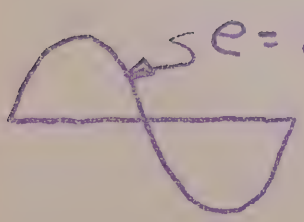
2. FLUX CHANGE RELATED TO APPLIED VOLTAGE

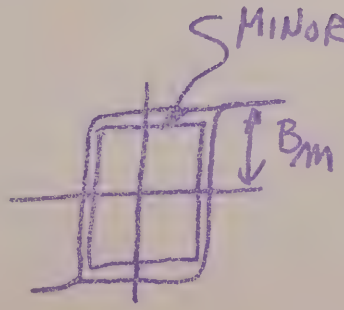


$$e = N\frac{d\phi}{dt}$$

$$\Delta\phi = \frac{1}{N}\int_0^t e\,dt$$

$$e = E_p \sin \omega t$$





$$\Delta\phi = \frac{1}{N}\int_0^{t=\pi/\omega} E_p \sin \omega t \, dt = \frac{2E_p}{\omega N} = \frac{E_p}{\pi f N}$$

$$E_p = \pi f N \Delta\phi$$

$$= \pi f N (2 B_m A)$$

$$E_{RMS} = \frac{E_p}{\sqrt{2}} = 4.44 f N A B_m$$

FOR SINE WAVE AND LOW SOURCE IMPEDANCE.

3. CURRENT RELATED BY B-H LOOP

FOR GIVEN FLUX, CURRENT DETERMINED FROM B-H LOOP.

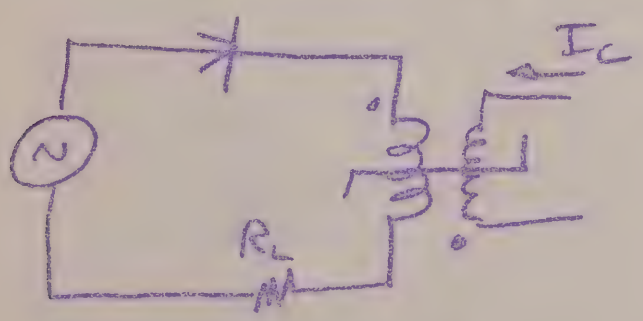
$$I = \frac{Hl}{N}$$

MKS

$$I = \frac{Hl}{0.4\pi N}$$

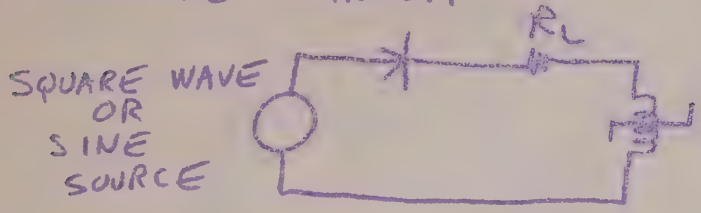
CGS

4. SELF-SATURATING MAGNETIC AMPLIFIER

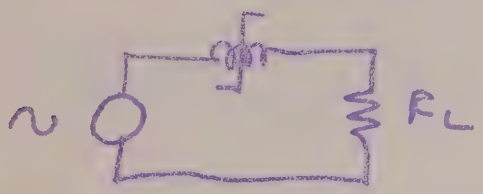


MAGNETIC APPLICATIONS

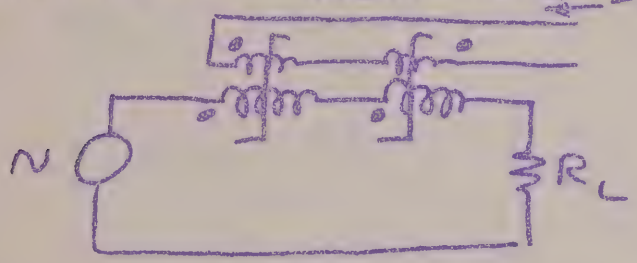
1. COUNTING CIRCUIT



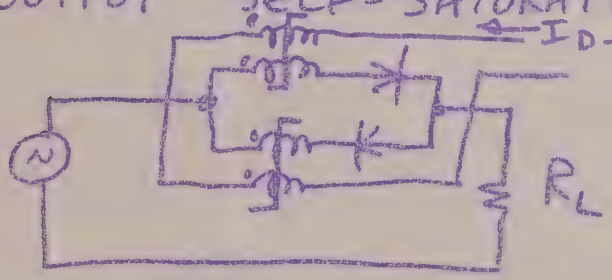
2. CONSTANT CURRENT SOURCE



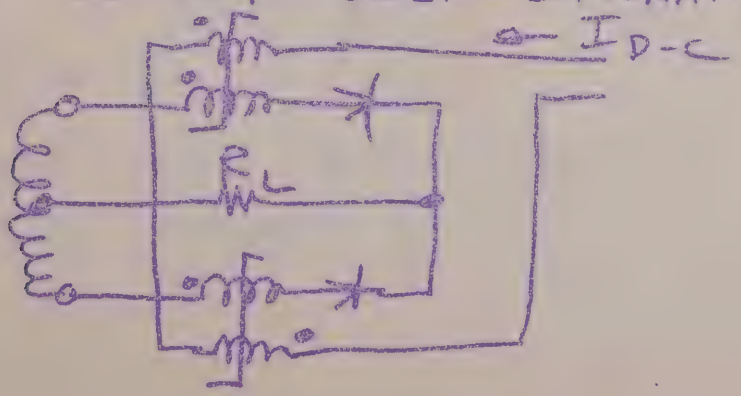
3. SATURABLE REACTOR



4. A-C OUTPUT SELF-SATURATING MAGNETIC AMPLIFIER

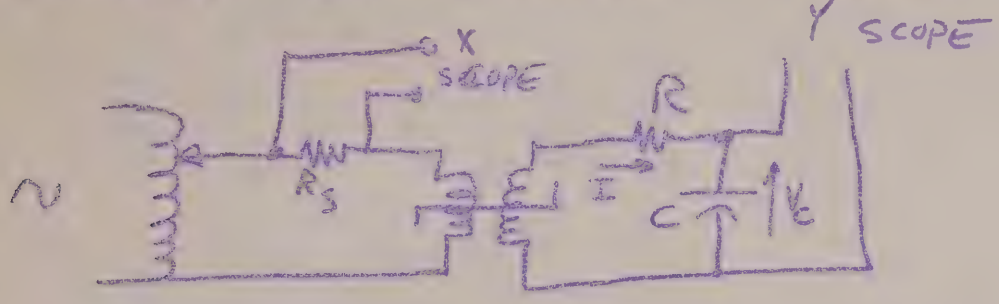


5. D-C OUTPUT SELF-SATURATING MAGNETIC AMP



DETERMINING CORE CHARACTERISTICS

1. DISPLAY OF DYNAMIC LOOPS



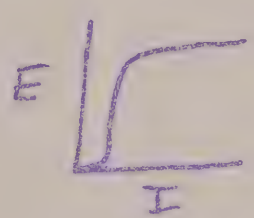
$$I(j\omega) = \frac{E(j\omega)}{R - j\frac{1}{\omega C}}$$

FOR $R \gg \frac{1}{\omega C}$

$$I(j\omega) \cong \frac{E(j\omega)}{R}$$

$$V_c(j\omega) = \frac{E(j\omega)}{R}\left(-j\frac{1}{\omega C}\right) = \frac{E(j\omega)}{RWC}(-j)$$

2. E - I CURVE



3. POWER, VA, AND PHASE SHIFTS WHEN EXCITING CORES.

T. B. 10/1/63

MAGNETIC CORES AVAILABLE FOR LABORATORY USE

A. Deltamax (Orthonol) 2 Mil

1. Qty - 5 51042-2A
   Core Area - 2.73 sq. cm.
   Mean Path - 23.99 cm.
   Windings -
   1) 600 T/ No. 24
   2) 600 T/ No. 24
   3) 600 T/ No. 24
   4) 600 T/No. 24
   5) 300 T/No. 24
   6) 300 T/ No. 24

2. Qty - 8 51031 - 2A (1T4180-D2)
   Core Area - 0.690 sq. cm.
   Mean Path - 21.99 cm.
   Windings -
   1) 1000 T/No. 26
   2) 1000 T/No. 26
   3) 500 T/No. 26
   4) 500 T/No. 26
   5) 1000 T/No. 26
   6) 1000 T/No. 26

3. Qty - 2 51031-2A
   Windings -
   1) 1000 T/No. 25
   2) 1000 T/No. 25
   3) 1000 T/No. 25
   4) 1000 T/No. 25
   5) 1000 T/No. 25
   6) 1000 T/No. 25

CURRENT CARRYING CAPACITY AT 1000 CIR. MILS/AMP

#24 - 0.404 A.
#25 - 0.320 A.
#26 - 0.252 A

B. Permalloy (Hy-Mu 80) 2 Mil

1. Qty - 4 51017-2D (1T4178-P2)
   Core Area - 0.690 sq. cm.
   Mean Path - 17.87 cm.
   Windings -
   1) 1000 T/No. 25
   2) 1000 T/No. 25
   3) 500 T/No. 25
   4) 500 T/No. 25
   5) 300 T/No. 25
   6) 300 T/No. 25

2. Qty - 2 1T4180-SP2
   Windings -
   1) 1000 T/No. 26
   2) 1000 T/No. 26
   3) 500 T/No. 26
   4) 500 T/No. 26
   5) 1340 T/No. 26
   6) 1340 T/No. 26

C. Z Silectron 4 Mil

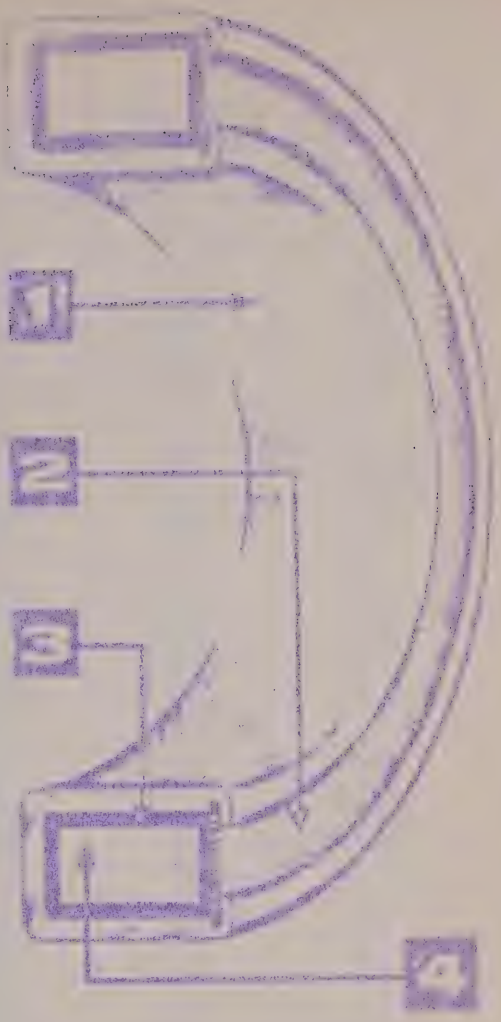
Qty -2 1T4178 -Z4
Windings -
1) 1000 T/No. 25
2) 1000 T/No. 25
3) 1000 T/No. 25
4) 1000 T/No. 25

D. Supermendur 4 Mil

Qty - 4 1T4180-R4
Windings -
1) 1000 T/No. 25
2) 1000 T/No. 25
3) 500 T/No. 25
4) 500 T/No. 25
5) 670 T/No. 25
6) 670 T/No. 25

features of the

Aluminum Core Box† Construction



1. ALUMINUM CORE BOX†

The special design of the aluminum box gives the completed core a structural strength far greater than any previously obtained for cores in plastic boxes. This is a most important factor in preventing deflection of the cores in the winding operation, for deflection and distortion often result in a marked change in magnetic properties of the core material. The core box is covered with an insulating coating to prevent the windings from shorting to the case.

2. SILICONE GLASS INSERT

The silicone glass insert, along with the aluminum box, permits the cores to withstand temperatures to *at least* 450° F. This is a vital design factor, especially in compact aircraft equipment. Because the aluminum can be sealed after the core is in place, a vacuum-tight barrier is provided. Vacuum impregnation of the coils is thus made completely safe.

3. INERT CUSHIONING

Surrounding the tape wound core inside the box is an inert "cushioning" material. This "cushion" acts to prevent vibration and shock from being transmitted into the magnetic material in such fashion as to adversely affect magnetic properties.

4. MAGNETIC MATERIALS

Magnetics, Inc. manufacturers Performance-Guaranteed Tape Wound Cores in Aluminum Core Boxes using all commercially available alloys, as shown in Table A. On special order, cores made from other magnetic alloys of special composition can be produced.

TABLE A — BASIC ALLOY WEIGHT COMPOSITIONS OF COMMERCIAL MAGNETIC MATERIALS

Trade Name	% Ni	% Fe	Other	Grain Structure	Flux Density Gausses	Resistivity Microhm-Cm	Curie Point 0°C	Density Grams/cc
[illegible]	79	17	4 Mo	"random"	8,700	57	420	8.72
48 Alloy	48	52		"random"	16,000	45	500	8.3
[illegible]	50	50		oriented	15,500	45	500	8.25
[illegible]		97	3 Si	oriented	20,000	48	700	7.65

TABLE B — TRADE NAMES OF SIMILAR MATERIALS

Hy-Mu 80	48 Alloy	Orthonol	Magnesil
[illegible]	[illegible]	[illegible]	Amco Oriented †
Mo-Permalloy	Allegheny 4750	Permenorm	Hypersil
[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	[illegible]

†This material has a different composition than the others in the same column. The characteristics of this material are such that in general it is not recommended for use in tape wound cores.

All *Performance-Guaranteed* [illegible] Magnetics, Inc. "Performance-Guaranteed" Tape Wound Cores are guaranteed to meet your performance specifications. These are truly the most economical tape wound cores offered to industry today, for their guaranteed performance effects major savings on your production line.

MAGNETICS inc.

TABLE II
TAPE WOUND CORE SIZES

AlCo. Part No.	Nominal Core Size (Inches)			Nominal Case Dimensions for Nos. 1 and 2 Type Cases (Inches)		
	I.D.	O.D.	H	(Minimum) I.D.	(Maximum) O.D.	(Maximum) H
*T 8043	0.500	0.825	0.125	0.421	0.709	0.253
*T 5340	0.500	0.750	0.125	0.396	0.634	0.253
T 2522	0.500	0.770	0.250	0.396	0.634	0.378
*T 5955	0.625	1.000	0.188	0.521	0.834	0.315
*T 5531	0.625	1.000	0.250	0.521	1.104	0.378
*T 5515	0.650	0.900	0.125	0.546	1.004	0.253
T 6150	0.650	1.150	0.375	0.546	1.254	0.503
*T 5502	0.750	1.000	0.250	0.646	1.104	0.378
*T 5504	0.750	1.125	0.188	0.646	1.229	0.315
T 5782	0.750	1.250	1.000	0.646	1.454	1.128
*T 4168	1.000	1.250	0.125	0.896	1.354	0.253
*T 7890	1.000	1.250	0.250	0.896	1.354	0.378
*T 4525	1.000	1.375	0.250	0.906	1.479	0.383
*T 5800	1.000	1.500	0.250	0.896	1.604	0.383
*T 5233	1.000	1.500	0.375	0.896	1.604	0.508
*T 6547	1.000	1.500	0.500	0.896	1.604	0.633
T 5778	1.125	1.625	0.500	1.021	1.729	0.633
*T 5367	1.250	1.750	0.250	1.146	1.854	0.383
*T 7441	1.250	1.750	0.500	1.146	1.854	0.633
T 7189	1.250	1.750	1.000	1.146	1.854	1.132
*T 5772	1.250	2.000	0.375	1.146	2.104	0.508
*T 6320	1.500	2.000	0.500	1.396	2.104	0.661
*T 4179	1.525	2.000	0.250	1.421	2.104	0.383
T 6114	1.625	2.000	0.500	1.521	2.006	0.633
*T 4178	2.000	2.500	0.500	1.896	2.604	0.661
*T 6110	2.000	3.000	0.500	1.896	3.134	0.661
*T 8027	2.000	3.000	1.000	1.896	3.134	1.161
*T 4180	2.500	3.000	0.500	2.396	3.134	0.661
*T 6109	2.500	3.500	0.500	2.396	3.634	0.661
*T 5465	2.500	3.500	1.000	2.396	3.634	1.161

*AIEE Preferred Core Sizes.

†These dimensions include an allowance of 0.008" per side for insulation of the core box prior to wire winding.

The type of core case required is designated as a prefix to the AlCo. part number:

Numeral Designation	Type of Core Case
1	Aluminum, Silicone Grease Filled
2	Aluminum, Oil-Filled, Hermetically Sealed
3	Nylon, Silicone Grease Filled
4	Nylon, Oil-Filled, Hermetically Sealed
5	Phenolic, Silicone Grease Filled

The material thickness for any tape wound core is added as an affix to the part number in accordance with the following table:

2.004".....	4
0.002".....	2
0.001".....	1

The material identification for Supermendur is the letter S. Composite designations are D for Deltamax, S for Supermalloy and L for Silectron.

A typical Supermendur core made from 4 mil material in a silicone grease filled aluminum case would be specified as part number 1T4179.S4.

STANDARD SIZES

of Performance-Guaranteed Tape Wound Cores

A_p Size $\times 10^{-4}$ (See Note 1)	CORE NUMBER (See Note 2)	CORE DIMENSIONS (In.)			NOMINAL CASE DIMENSIONS (In.)			CASE WINDOW AREA IN CIRCULAR MILS $\times 10^{3}$	MEAN LENGTH OF MAGNETIC PATH (Cm.)	EFFECTIVE CORE CROSS SECTION AREA ($Cm.^2$)			I.D./O.D. RATIO
		I.D.	O.D.	Ht.	I.D.	O.D.	Ht. (See Note 3)			.001	.002	.004 & .006	
0.021	50159	0.375	0.500	0.125	0.315	0.560	0.195	0.098	3.49	0.041	0.043	0.046	0.750
*0.008	50056	0.500	0.625	0.125	0.440	0.685	0.195	0.194	4.47	0.040	0.043	0.045	0.800
0.013	50057	0.625	0.750	0.125	0.555	0.810	0.195	0.308	5.48	0.040	0.042	0.046	0.833
*0.017	50009	0.500	0.750	0.125	0.440	0.810	0.195	0.194	4.92	0.081	0.086	0.091	0.667
*0.030	50002	0.650	0.900	0.125	0.390	0.960	0.195	0.348	6.13	0.081	0.086	0.091	0.722
0.053	50033	0.625	0.875	0.250	0.555	0.945	0.330	0.308	5.99	0.162	0.172	0.182	0.714
0.059	50003	0.750	0.938	0.250	0.680	1.010	0.330	0.460	6.74	0.121	0.128	0.135	0.800
*0.059	50076	0.625	1.000	0.188	0.555	1.070	0.268	0.308	6.36	0.182	0.193	0.205	0.625
*0.074	50011	1.000	1.250	0.125	0.930	1.320	0.195	0.864	8.94	0.081	0.086	0.091	0.800
*0.079	50007	0.625	1.000	0.250	0.555	1.070	0.330	0.308	6.36	0.242	0.257	0.272	0.625
*0.079	50061	0.750	1.000	0.250	0.680	1.070	0.330	0.462	6.93	0.161	0.171	0.181	0.750
*0.089	50105	0.750	1.125	0.188	0.680	1.195	0.260	0.462	7.38	0.182	0.193	0.205	0.667
0.118	50168	0.750	1.000	0.375	0.680	1.070	0.455	0.462	6.97	0.227	0.257	0.272	0.750
0.119	50094	0.625	1.000	0.375	0.555	1.070	0.445	0.308	6.49	0.339	0.385	0.411	0.625
*0.148	50004	1.000	1.250	0.250	0.930	1.320	0.330	0.864	8.94	0.161	0.171	0.181	0.800
0.178	52034	0.750	1.125	0.375	0.680	1.195	0.455	0.460	7.49	0.342	0.389	0.405	0.667
0.186	50115	1.125	1.375	0.250	1.045	1.445	0.330	1.090	9.99	0.161	0.171	0.181	0.818
*0.222	50029	1.000	1.375	0.250	0.930	1.445	0.330	0.864	9.39	0.242	0.257	0.272	0.727
0.237	50188	0.750	1.250	0.375	0.680	1.320	0.455	0.462	7.98	0.453	0.514	0.544	0.600
0.250	50181	0.875	1.250	0.375	0.805	1.320	0.440	0.648	8.48	0.340	0.386	0.408	0.700
*0.296	50032	1.000	1.500	0.250	0.930	1.570	0.330	0.864	9.84	0.323	0.343	0.363	0.667
*0.444	50026	1.000	1.500	0.375	0.930	1.570	0.445	0.864	9.84	0.484	0.514	0.544	0.667
*0.469	50030	1.250	1.750	0.250	1.170	1.820	0.330	1.358	11.85	0.323	0.343	0.363	0.714
*0.592	50038	1.000	1.500	0.500	0.930	1.570	0.590	0.864	9.84	0.605	0.685	0.726	0.667
*0.937	50018	1.625	2.000	0.250	1.525	2.100	0.330	2.324	14.41	0.242	0.257	0.272	0.813
*0.937	50035	1.250	1.750	0.500	1.170	1.820	0.590	1.368	11.85	0.605	0.685	0.726	0.714
*1.055	50425	1.250	2.000	0.375	1.170	2.100	0.465	1.368	12.60	0.726	0.771	0.817	0.625
*2.471	50017	2.000	2.500	0.500	1.900	2.600	0.590	3.608	17.87	0.805	0.685	0.726	0.800
2.685	50040	1.500	2.000	1.000	1.400	2.100	1.110	1.960	13.99	1.211	1.370	1.457	0.750
*2.686	50001	1.500	2.500	0.500	1.400	2.600	0.590	1.959	15.79	1.210	1.371	1.452	0.600
*3.944	50031	2.500	3.000	0.500	2.400	3.100	0.590	5.757	21.73	0.605	0.685	0.726	0.833
*4.947	50103	2.000	3.000	0.500	1.900	3.100	0.590	3.608	19.67	1.210	1.371	1.452	0.667
*7.328	50128	2.500	3.500	0.500	2.312	3.688	0.713	5.343	23.71	1.210	1.371	1.452	0.714
*8.883	50022	2.000	3.000	1.000	1.900	3.100	1.110	3.608	19.67	2.419	2.742	2.903	0.667
*14.801	50042	2.500	3.500	1.000	2.313	3.688	1.188	5.343	23.71	2.419	2.742	2.903	0.714
*22.207	50048	2.500	3.750	1.250	2.313	3.938	1.437	5.347	26.59	3.780	4.284	4.536	0.667
*27.489	50100	2.500	3.750	1.500	2.313	3.938	1.688	5.347	26.59	4.536	5.141	5.444	0.667
*48.176	50081	3.250	4.500	1.500	3.062	4.688	1.688	9.371	30.64	4.536	5.141	5.444	0.722
*87.452	50427	3.250	5.000	1.500	3.062	5.188	1.688	9.371	32.40	6.351	7.198	7.621	0.650
*99.827	50112	4.000	5.250	2.000	3.782	5.469	2.280	14.063	36.66	6.048	6.855	7.258	0.762
*150.385	50426	4.000	6.000	2.000	3.782	6.200	2.276	14.532	39.34	9.677	10.968	11.613	0.667

*E.I.A. Proposed Standard Size.

Note 1—Product of window area and iron area calculated for 2 mil material.
Note 2—Part numbers listed are for phenolic cases. Specify 51000 series for aluminum cases (last three numbers remain the same).
Note 3—Dimensions listed are nominal sizes for phenolic cases. For aluminum cases, add .015 to .020 inches to heights shown.

FIG. 6

SUPERIMPOSED TYPICAL 60-CYCLE DYNAMIC LOOPS

OF HY MU 80, 48 ALLOY AND ORTHONOL

MAGNETICS

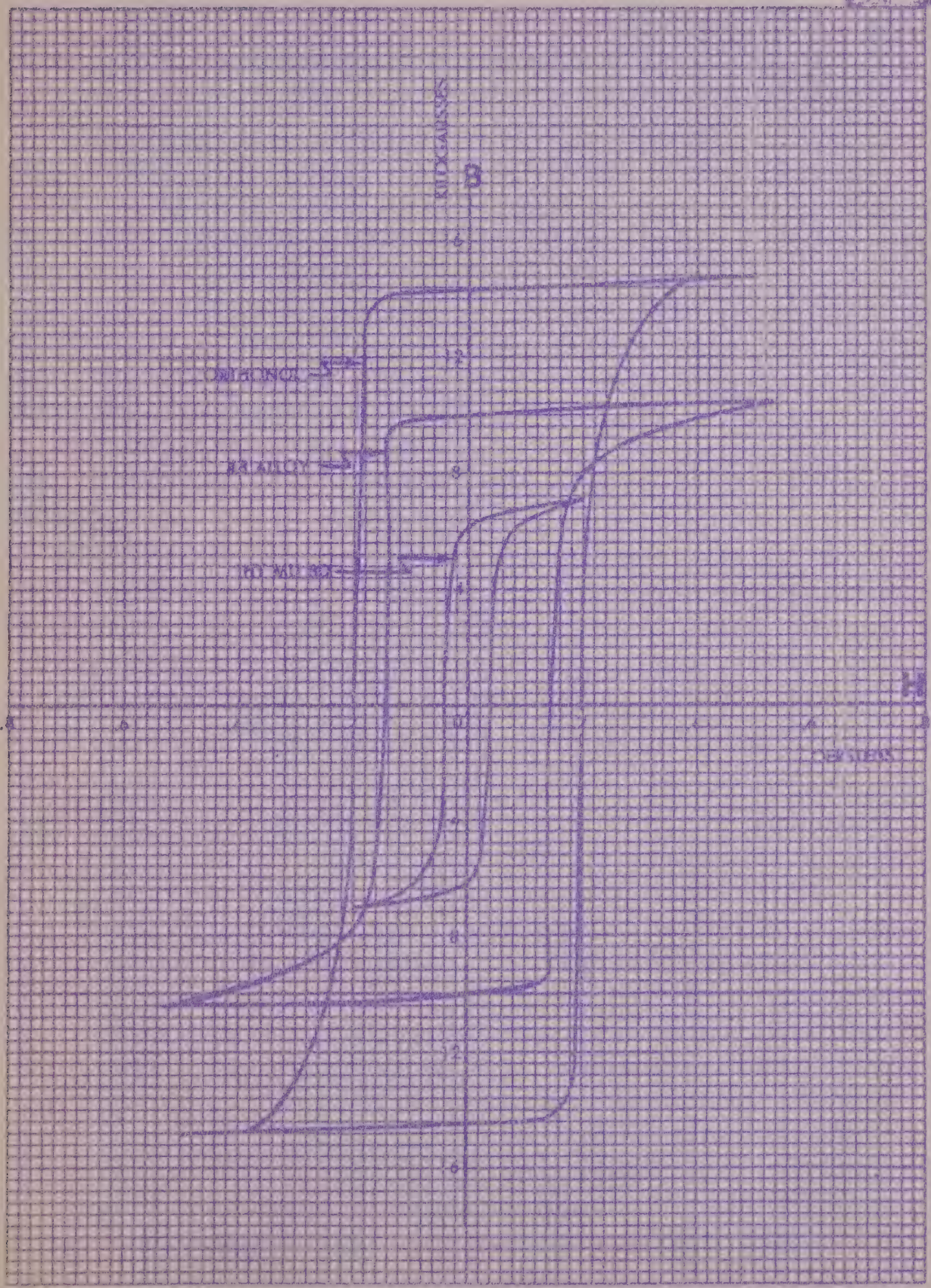
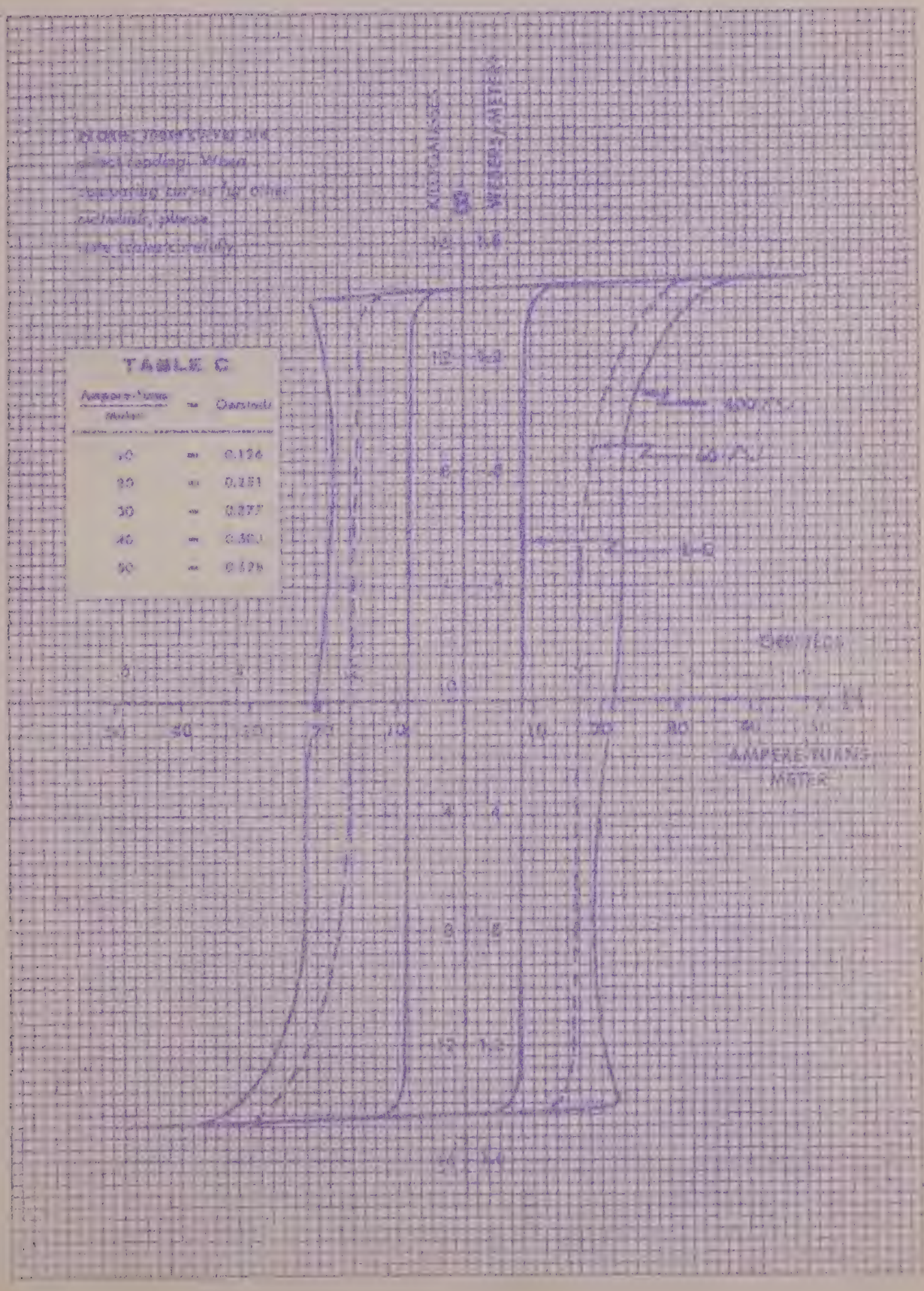


FIG. 7

Typical D.C. Hysteresis Loop and A.C. Dynamic Loops

1⅝" x 2" x ¼" x .002" Tape Wound Core

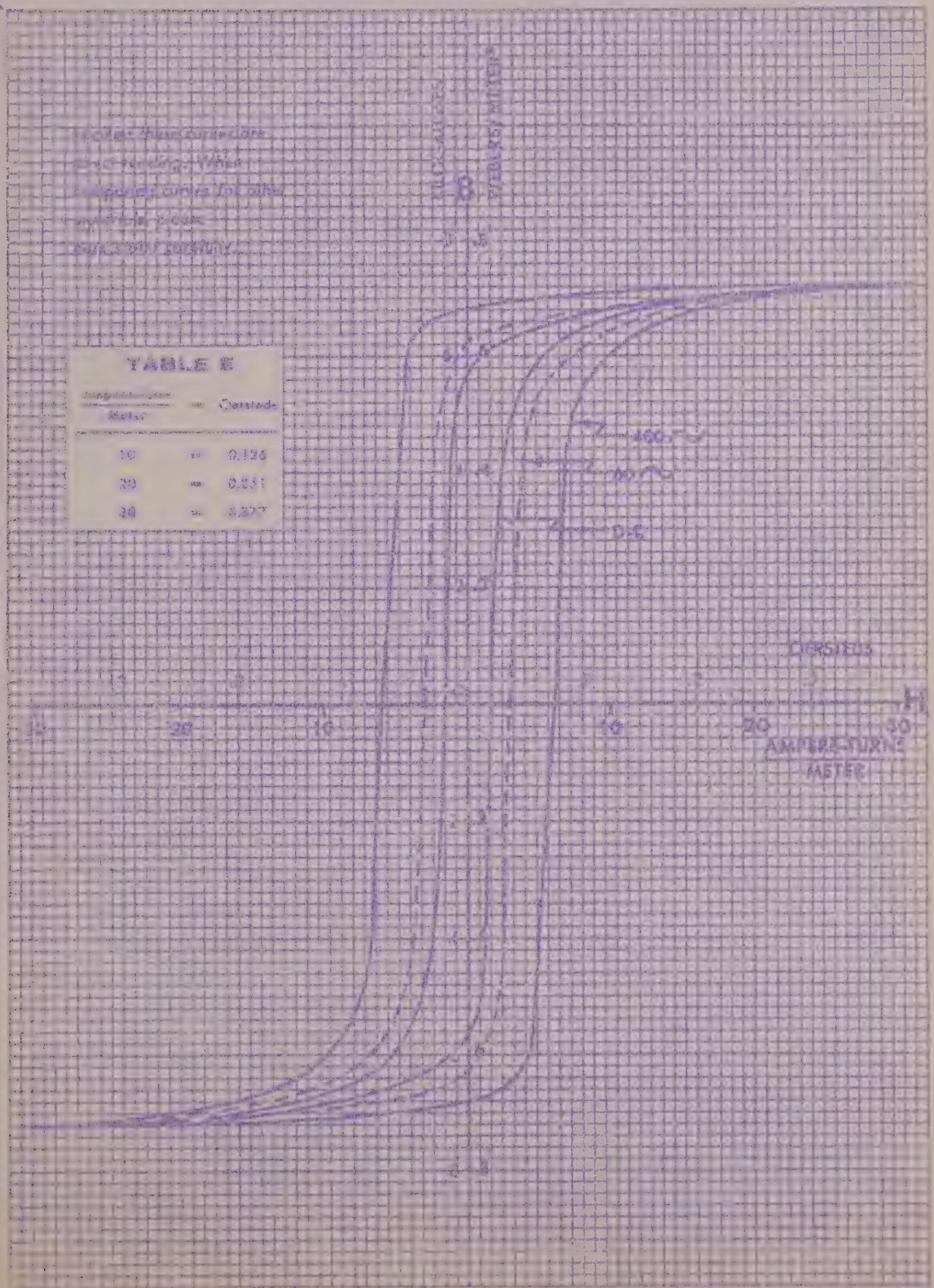
μ_{max} = 127,300



Typical D.C. Hysteresis Loop and A.C. Dynamic Loops

1⅛" x 2" x ⅛" x .0½" Tape Wound Core

d-c μ_{max} = 148,000



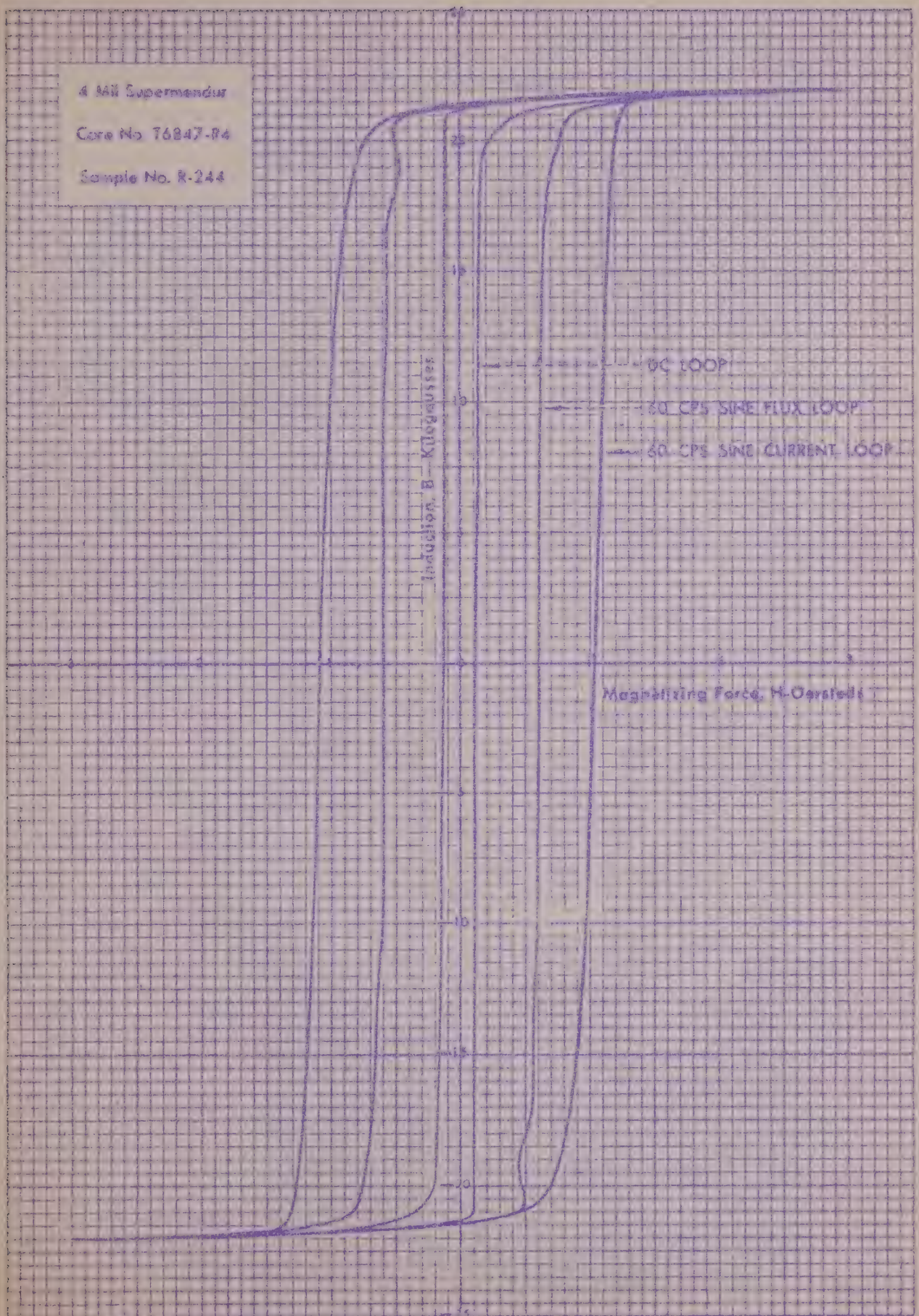


Figure 1 Comparison of Typical DC and 60 CPS Hysteresis Loops of 4 Mil Supermendur Cores.

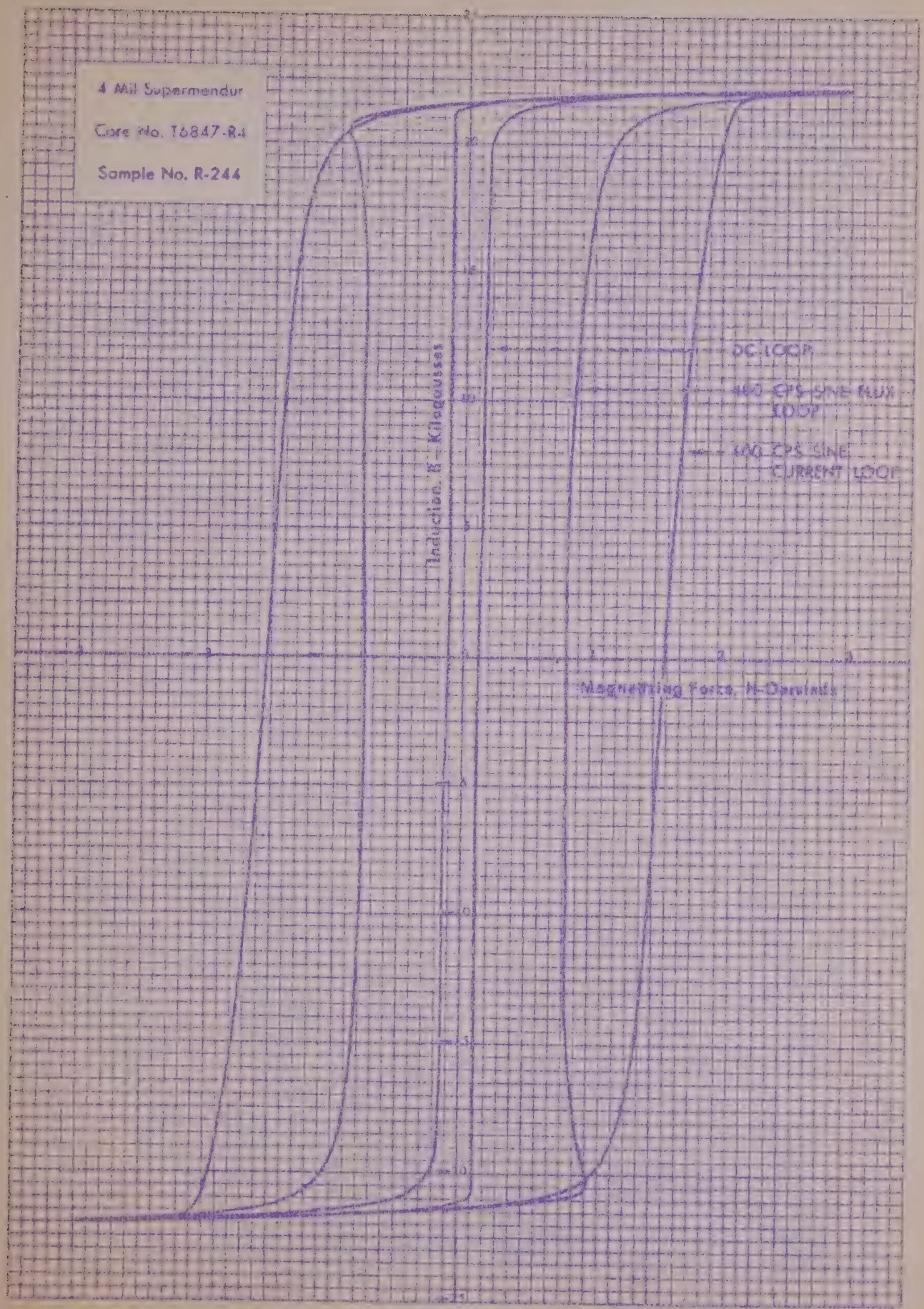


Figure 2. Comparison of Typical DC and 400 CPS Hysteresis Loops of 4 Mil Supermendur Cores.

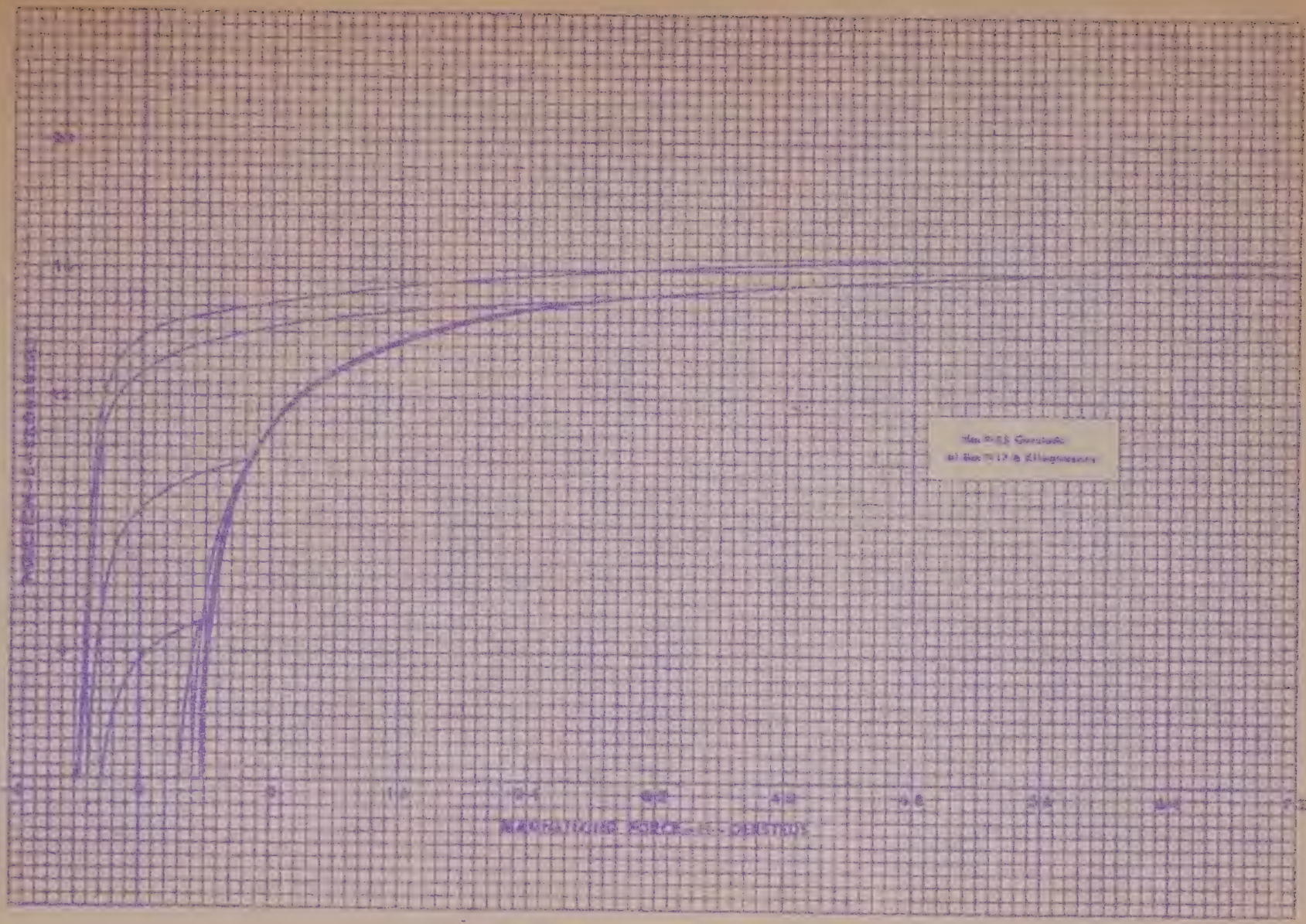


FIG. 18—TYPICAL DC HYSTERESIS LOOPS
OF 4 MIL SILECTRON UNCUT CORES—IMPREGNATED

Adjust ferrite-core constants, to suit your coil design needs. You needn't be limited to those shapes and sizes you find in the catalogs—calculate your own.

The effective properties and dimensional core constants of magnetic materials for coils as supplied by ferrite-core manufacturers enable engineers to perform speedy and practical coil designs. Working with the basic material properties found in physicists' materials tables, engineers would find predicting in-circuit performance very difficult, if not impossible.

Instead of complicated formulas for determining coil inductance, most ferrite magnetic-core manufacturers supply core constants and an inductance factor, A_L, for particular core types and dimensions (Fig. 1). The inductance of a coil wound on a core can be figured to a respectable degree of accuracy with

$$L = A_L N^2 \text{ (nanohenries)}. \quad (1)$$

However, the given A_L values are accurate only for the specific applications and flux densities that the core is tested and rated for—filters, pulse-transformers, power-inverters, etc.[1]

So manufacturers also make it easy to calculate the operating, or effective flux density, B, by supplying a core's effective area, A_e, as well as effective volume, V_e. You simply use the following equation:

$$B = E\ (10^8)/4.44\ fNA_e \text{(gauss)}, \quad (2)$$

where

E = rms volts,
f = frequency in Hz,
N = number of turns,
A_e = effective core area in cm^2.

To get the effective field strength, H_e, in the core or its air gap, if any, you need to know the effective length of the magnetic path, d_e, in cm. Use the following equation:

$$H_e = 4\pi\ NI/10d_e \text{ (oersteds)},$$

where I is the current in amperes through the coil. Again, manufacturers make the calculation easy by supplying values of d_e for their various core designs.

Cores don't always fit your needs

But what if listed core dimensions don't quite fit your needs? How can you adjust their dimensional constants to get the performance you want?

The equation for inductance also can be expressed with

$$L = 4\pi\ N^2\mu_e\ (10^9)/C_1, \quad (3)$$

where

μ_e = effective permeability,
C_1 = a dimensional core constant.

Change the constant C_1, and you can change the inductance for a given core-material permeability. Clearly, from Eqs. 1 and 3,

$$A_L = 4\pi\ \mu_e\ (10^9)/C_1.$$

The core constant C_1, supplied by manufacturers for specific core sizes, can be calculated[2] from the summation,

$$C_1 = \sum_{i=1}^{n} d_i/A_i.$$

For a uniform toroid (Fig. 2a), then,

$$C_1 = \int_{r_1}^{r_2} 2\pi\ r/(h \cdot dr)$$

$$= 2\pi/h \cdot \log_n(r_2/r_1). \quad (4)$$

For a more complex core, say, with four identifiable sections as in Fig. 2b, you must sum the separate sections. Therefore,

$$C_1 = \sum_{i=1}^{4} \frac{d_i}{A_i} = \frac{d_1}{A_1} + \frac{d_2}{A_2} + 2\,\frac{d_3}{A_3}.$$

Note that sections 3 and 4 are identical and combined in the last term.

In section 1, using the methods of Eq. 4, since

$$\frac{d_1}{A_1} = \pi/h \cdot \log_n(r_3/r_1).$$

In section 2, since $d_2 = (\pi - 2\phi)\ r_b$, then

$$\frac{d_2}{A_2} = (\pi - 2\phi)/h \cdot \log_n(r_2/r_1).$$

And in sections 3 and 4, to simplify calculations, since ø is relatively small, r_3 and r_2 can be averaged (Fig. 2c) and the approximate answer you obtain will cause little error. Then,

$$2\,\frac{d_3}{A_3} \approx 20/[h \cdot \log_n(r_2 + r_3)/2r_1]$$

Changes in the core dimensions—radii r_1, r_2, r_3 and

Michael I. Distefano, Manager of Quality Engineering, Indiana General Electronic Products, Crows Mill Rd., Keasbey, NJ 08832.

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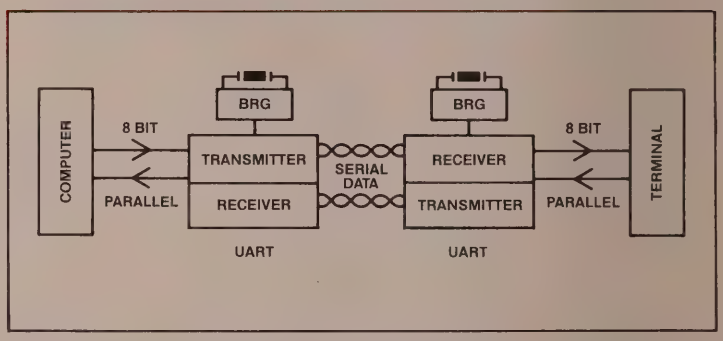

HD-4702/6405 FEATURES

- CMOS
- TTL Compatible
- Low Power Dissipation: 4.0mW TYP. (6405); 4.5mW TYP. (4702)
- Conforms to EIA RS-404
- One unit controls up to eight transmission channels
- On-chip input pull-up circuit (4702 only)
- 16 pin Cerdip and Epoxy dual-in-line packages
- Second source available

HD-6402/6402A FEATURES

- CMOS
- Operation from D.C. to 4.0MHz
- Low power—TYP. 10 mW @ 2.0MHz
- 4V to 11V operation
- Programmable word length, stop bits and parity
- Automatic data formatting and status generation
- Compatible with industry standard UART's
- Second source available

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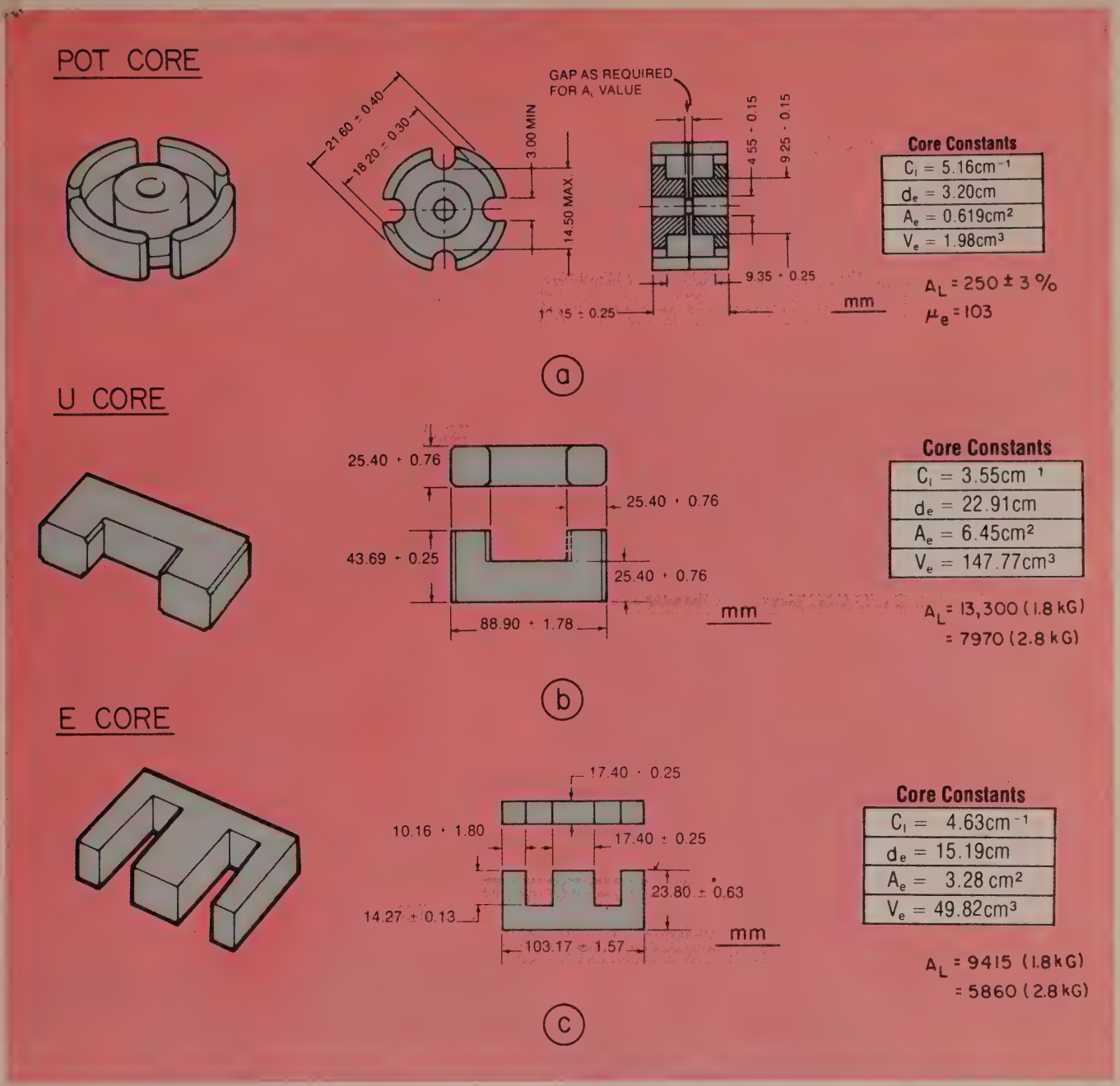
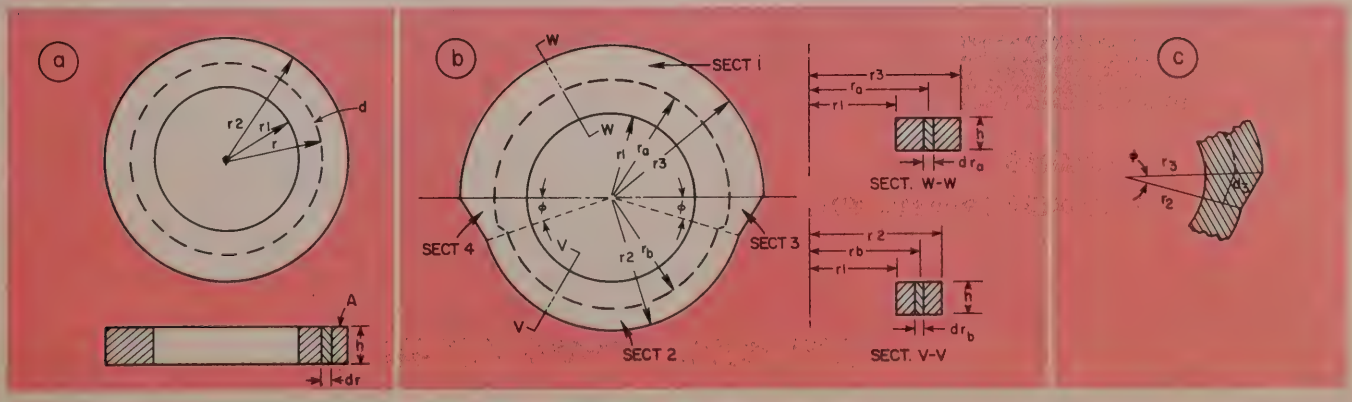
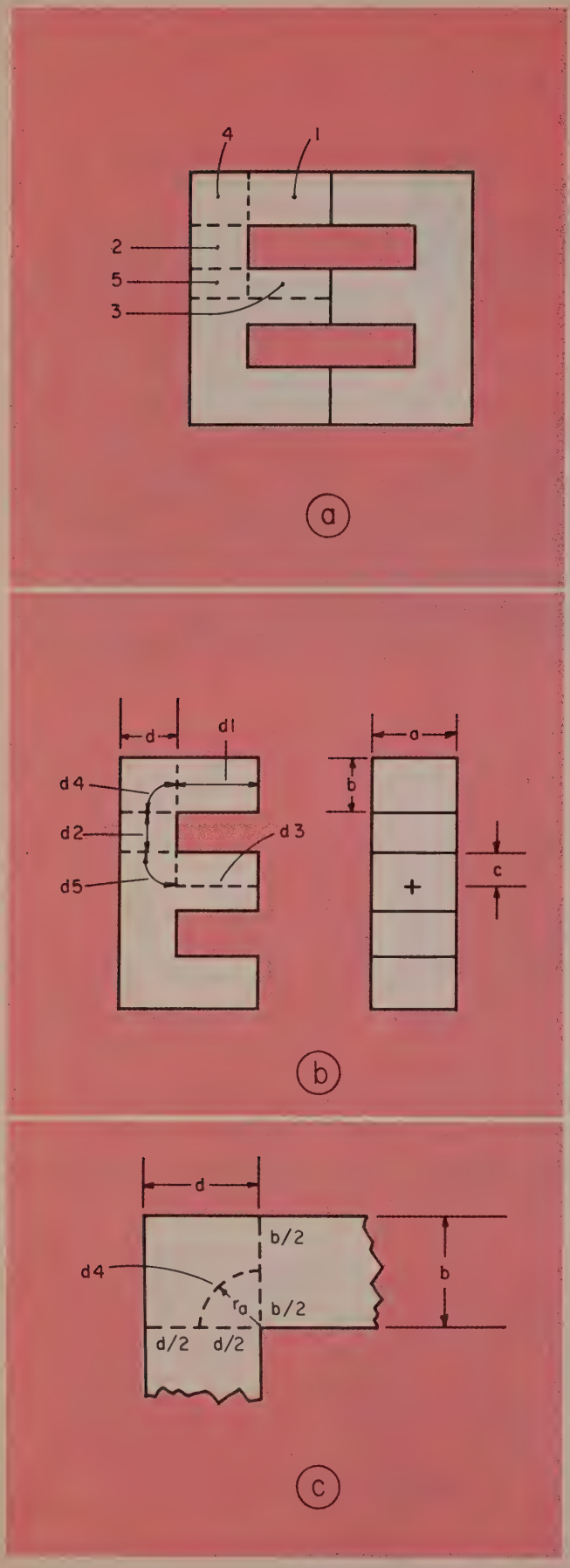


1. **Ferrite coil and transformer cores** are usually specified in manufacturers' catalogs with effective values for both their magnetic and dimensional constants. Effective values enable you to quickly design practical components.



2. **A simple toroid core** (a) is easily evaluated to determine its important dimensional core constants, C_1, d_e and A_e. But more complex shapes (b) require that you sum the various sections and make approximations (c) for some of the irregularly shaped parts. Core-constant equations allow you to adjust the dimensions as needed.



3. **In evaluating the core constants for an E core** (a), you can take advantage of its symmetry (b) and approximate the effective dimensions of the corner sections (c) to simplify the calculations.

angle ø—can now be translated into their effect on C_1 and, in turn, their effect on A_L and inductance.

Solving the constant for E cores

A similar procedure for E cores provides the relationship between C_1 and the core's physical dimensions. For a pair of E cores with a rectangular cross section, you need consider only five sections, since the two Es are identical. And because each E is symmetrical, the area of the magnetic path in each half-E is in parallel with the other half, but in series with its counterpart in the other section of the pair; thus,

$$C_1 = \sum_{i=1}^{5} \frac{d_i}{A_i}$$

In Fig. 3b, the dimensions of d_1, d_2 and d_3 are obviously the lengths as shown. However, d_4 and d_5 need some special treatment.

A good approximation for d_4 is to use one-quarter the circumference of the mean circle whose radius, r_a, is the average of b/2 and d/2 (Fig. 3c); consequently,

$$d_4 = 1/4\ (2\pi)\ r_a$$

$$= 1/4\ (2\pi)\left(\frac{b/2 + d/2}{2}\right)$$

$$= \frac{\pi}{8}\ (b + d).$$

Similarly,

$$d_5 = \frac{\pi}{8}\ (c + d).$$

The areas, A_i, associated with sections 1, 2 and 3 are clearly,

$$A_1 = ab$$
$$A_2 = ad$$
$$A_3 = ac.$$

But for sections 4 and 5, you must make another approximation: Use the average of the sections' terminating cross-section areas, so that

$$A_4 = (1/2)\ (ab + ad),$$
$$A_5 = (1/2)\ (ac + ad).$$

Now, the complete expression for C_1 can be written as

$$C_1 = \frac{d_1}{ab} + \frac{d_2}{ad} + \frac{d_3}{ac} + \frac{\pi}{4}\left(\frac{b + d}{ab + ad}\right) + \frac{\pi}{4}\left(\frac{c + d}{ac + ad}\right)$$

With these examples of how C_1 is related to core dimensions and geometry, you should now be able to derive your own relationships for other core shapes. Once you have determined the equation—even an approximate one—you can then decide how to adjust the dimensions to your needs, and tell a manufacturer exactly what you want. ■■

References

1. Van der Poel, J. M., "Improve Inductor Design Accuracy," *Electronic Design*, Feb. 2, 1976, pp. 58-62.

2. *"Calculation of the Effective Parameters of Magnetic Piece Parts,"* Publication 205, IEC Standard, International Electrotechnical Commission (ISO), Geneva, Switzerland.

Design power inductors step by step.

Concentrate on the power dissipated in the windings instead of iterating hard-to-determine magnetic characteristics.

When efficiency, size and cost requirements dictate power inductors for filtering, relax. There's a straightforward and exact alternative to the indirect and vague design procedures normally used. To design an efficient power choke fast, and without being bogged down in the tedious repetition of conventional iterative processes, just follow 11 steps that focus on optimizing the magnetic characteristics:

1. Determine the total current.
2. Select the core material.
3. Determine the optimum flux density and magnetic-field strength.
4. Select the minimum-sized magnet wire.
5. Determine the minimum effective volume.
6. Select the minimum-sized core.
7. Determine the number of turns.
8. Determine the air gap.
9. Check the incremental effect.
10. Determine the total power loss.
11. Determine the maximum operating temperature the inductor must withstand.

Follow this step-by-step method to determine the optimum magnetic characteristics without the usual lengthy iteration. The power dissipated in the coil's windings then becomes the major factor that limits the inductor's minimum size.

Finding the coil current

But before you can start, distinguish between the maximum incremental current, I_m, and the rated current at maximum temperature, I_r. The incremental current is the total instantaneous ac or pulse current (I_{pk}) and dc offset or bias (I_{dc}):

$$I_m = I_{pk} + I_{dc} \quad (1)$$

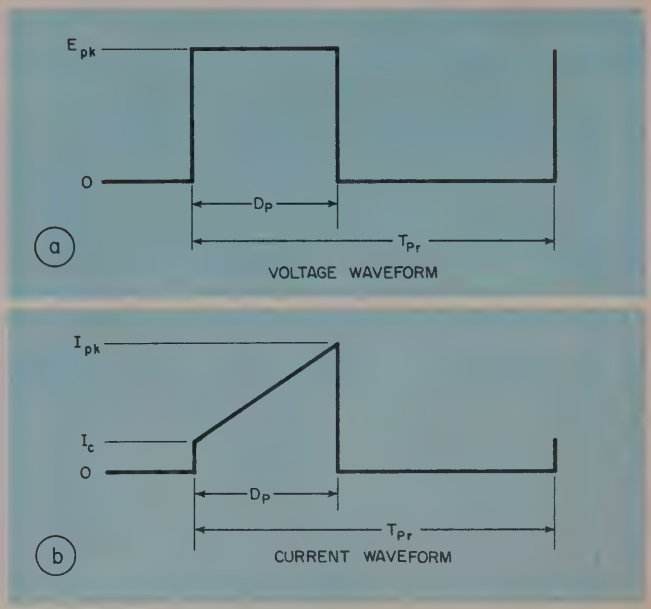
Since these currents together change the choke's inductance, the minimum inductance is determined by I_m.

The rated current is the total effective ac, I_{eff}, and I_{dc}:

$$I_r = I_{eff} + I_{dc} \quad (2)$$

These currents heat the inductor, so I_r determines the minimum size of the magnet wire.

Walter V. Manka, Senior Design Engineer, American Precision Industries Inc., 270 Quaker Rd., Box 130, East Aurora, NY 14052



1. A trapezoid of current (a) results when a square wave of voltage (b) is impressed on an inductor. The initial jump of current, I_c, ramps up to the final value, I_{pk}, with a slope that depends on coil inductance and resistance.

With a sine wave of E_{ac}, the maximum rms voltage across the choke, I_{eff} depends on L_m, the incremental inductance at I_m, and the operating frequency, f:

$$I_{eff} = E_{ac}/2\pi f L_m \quad (3)$$

also

$$I_{pk} = \sqrt{2}\, I_{eff}. \quad (4)$$

Be careful in assigning a value to f—it may not be the line frequency. For instance, with a 60-Hz three-phase full-wave-bridge rectifier, f is 360 Hz.

For pulse excitation of the choke, as in switching regulators, the voltage and current waveforms are shown in Fig. 1. When a choke handles pulses rather than sine waves, I_{pk} depends on the pulse excitation voltage (E_{pk}), the pulse duration (D_p), the L_m and the core-loss current (I_c), which is due to hysteresis and eddies:

$$I_{pk} = (E_{pk}D_p/L_m) + I_c. \quad (5)$$

Choose the proper core and you can keep I_c less than 10% of I_{pk}:

$$I_c \leq 0.1\ I_{pk} \quad (5a)$$

The pulse-repetition time, t_{pr}, comes into play for I_{eff}.

$$I_{eff} = \sqrt{D_p\ (I_p^2 + I_{pk}I_c + I_c^2)/3\ t_{pr}} \quad (6)$$

Once you've determined the values for the ap-

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85 Executive Boulevard, Elmsford, New York 10523

CIRCLE NUMBER 32

Table 1. Average values of common core materials.

Material Designation	Freq. Range (Hz)	Temp. Range (°C)	U_i (G/Oe)	B_s (G)	B_r (G)	H_i (Oe)
Electrical Steels[4]						
Silicon Iron	20 to 1 k	−55 to +300	500	17.5 k	12 k	5.5
Silectron	20 to 10 k	−55 to +375	1.5 k	16.5 k	14 k	0.83
Alloy 48	20 to 8 k	−55 to +250	1 k	12.5 k	10 k	1.25
HY-MV 80	20 to 25 k	−55 to +230	10 k	8 k	4.4 k	0.18
Supermalloy	20 to 25 k	−55 to +230	50 k	7.3 k	4 k	0.033
Supermendur	20 to 2 k	−55 to +460	1.5 k	21 k	19 k	0.67
Molypermalloy Powders						
MPP 14[2]	400 kto 1 M	−55 to +250	14	6 k	10	214
MPP 26[2]	400 to 650 k	−55 to +230	26	6 k	10	115
MPP 60	400 to 250 k	−55 to +200	60	6 k	10	49.8
MPP 125	40 to 100 k	−55 to +200	125	6 k	200	23.2
MPP 160	40 to 70 k	−55 to +200	160	6 k	200	18.1
MPP 200	40 to 30 k	−55 to +175	200	6 k	200	14.5
MPP 300	40 to 25 k	−55 to +150	300	6 k	300	9.5
MPP 550	40 to 20 k	−55 to +125	550	6 k	650	4.86
Powdered Irons						
Carbonyl SF[2]	2 to 50 M	−55 to +125	7.5	8 k	10	533
Carbonyl E[2]	200 k to 10 M	−55 to +125	10	8 k	10	400
Carbonyl C[2]	100 k to 2 M	−55 to +125	20	8 k	10	200
Carbonyl GQ4[2]	50 k to 1 M	−55 to +125	35	8 k	10	114
Carbonyl HA	1 to 100 k	−55 to +105	60	8 k	2200	48.3
75 Powder	400 to 50 k	−55 to +105	75	8 k	2200	38.7
90 Powder	400 to 10 k	−55 to +105	90	8 k	2200	32.2
Ferrites[3]						
F40	10 to 80 M	−55 to +250	40	2400	750	20.6
F125	200 k to 10 M	−55 to +250	125	2350	1200	4.6
F175	100 k to 5 M	−55 to +230	175	2550	1400	3.28
F250	50 k to 4 M	−55 to +200	250	2200	1100	2.2
F400	10 k to 2.5 M	−55 to +175	400	2700	1100	2
F750	1 k to 1.5 M	−55 to +125	750	4000	1800	1.47
F1000	1 k to 1 M	−55 to +125	1000	4200	1700	1.25
F1500	1 k to 650 k	−55 to +125	1500	4000	1100	0.97
F2000	400 to 500 k	−55 to +125	2000	4400	1500	0.72
F2300	400 to 300 k	−40 to +105	2300	4000	1200	0.61
F2700	400 to 250 k	−30 to +105	2700	4700	2000	0.50
F5000	400 to 100 k	−25 to +105	5000	4300	1200	0.31
F10000	400 to 80 k	−25 to +90	10000	4300	1200	0.16

Notes:
(1) For specific data and tolerances, refer to individual suppliers. (2) Excessive heating occurs before incremental effects are observed. (3) There are no standard designations for equivalent materials between ferrite suppliers. Designation used is for convenience. (4) Frequency range of electrical steel depends on material thickness. The thinner the material, the higher the frequency range.

Glossary of inductor terms

Symbol	Terminology	Units
A_c	Cross-sectional area of the core	cm^2
A_{Lo}	Initial-inductance index	$H/turn^2$
A_{Lm}	Incremental-inductance index	$H/turn^2$
A_s	Total surface area	cm^2
B	Maximum operating-flux density	G
B_r	Residual-flux density	G
B_s	Saturation-flux density	G
C_v	Core loss per unit volume	W/cm^3
C_{vf}	Core-loss factor	$W/cm^3/Hz$
d_i	Insulated-wire diameter	in.
d_o	Bare-wire diameter	in.
D_p	Pulse duration	s
E_{ac}	Ac-excitation voltage	rms V
E_{pk}	Pulse-excitation voltage	pk V
f	Design operating frequency	Hz
G_t	Thermal conductance	W/°C
H	Maximum operating magnetic-field strength	Oe
H_i	Intrinsic magnetic-field strength	Oe
I_c	Core-loss current	A
I_{dc}	Dc current (offset or bias)	A
I_{eff}	Effective current	A
I_f	Fusing current	A
I_m	Maximum incremental current	A
I_{pk}	Pulse current	A
I_r	Rated current at max temperature	A
I_{ro}	Rated current at room temperature	A
k	Winding-utilization factor	---
L	Inductance	H
L_c	Magnetic-path length of the core	cm
l_e	Effective magnetic-path length	cm
l_g	Total air-gap length	cm
L_m	Incremental inductance at I_m	H
l_{tm}	Mean length per turn	ft
L_o	Initial inductance	H
N	Total turns	turns
p	Dc resistance per unit length	Ω/ft
P_c	Core loss	W
P_t	Total power	W
P_w	Winding loss	W
r	Thermal coefficient of resistance	Ω/Ω/°C
R_{dc}	Dc winding resistance	Ω
S_d	Surface dissipation	$W/cm^2/°C$
T_a	Ambient temperature	°C
T_m	Maximum operating temperature	°C
T_o	Reference temperature	°C
T_{pr}	Pulse-repetition time	s
T_r	Temperature rise	°C
t_{pi^2}	Winding density	$turns/in.^2$
U_e	Effective permeability	G/Oe
U_i	Initial permeability	G/Oe
U_m	Incremental permeability	G/Oe
V_e	Effective volume	cm^3
V_{em}	Minimum effective volume	cm^3
V_c	Actual core volume	cm^3
W_a	Winding cross-sectional area	cm^3

propriate coil currents, you can select a core material from the hundreds of magnetic materials available. Table 1 lists a representative cross-section of several popular core materials.

To pick the right core material, you need to know the required f, maximum operating temperature, T_m, core properties you need, cost, geometry and winding limitations, among other things. But whenever possible, and especially for switching regulators, use gapped-ferrite cores.

The core loss per unit volume, C_v, depends on the core-loss factor:

$$C_v = C_{vf}\, f \qquad (7)$$

The crux of this entire procedure is that it determines explicitly—without iteration—optimum values for maximum operating flux density, B, and maximum operating magnetic-field strength, H, for the selected core material. Empirical analysis has shown that incremental effects begin approximately when the intrinsic magnetic-field strength, H_i, equals the saturation-flux density, B_s, minus the residual-flux density, B_r, all divided by twice the initial permeability, U_i, or

$$H_i = (B_s - B_r)/2U_i \qquad (8)$$

Thus, for inductors passing substantial dc, you must lower the maximum operating flux density to the differential flux density, $B_s - B_r$, rather than just B_s:

$$B = B_s - B_r. \qquad (9)$$

Maximum operating field strength depends not only on B, but also on incremental permeability, U_m:

$$U_m = U_i L_m / L_o, \qquad (10)$$

where L_o is the choke's initial low-level ac value of inductance with no dc, and L_m is the desired inductance value at I_m.

Now you can find H:

$$H = B/U_m. \qquad (11)$$

Because of the large variations in the permeabilities of many magnetic materials, especially the electrical steels, specify U_i at no more than 40 G. And expect variations in U_i, B_s and B_r at high temperatures.

Minimizing magnet-wire size

Having found values for B and H, you can figure out the thinnest magnet wire that you can use.

The size of the magnet wire is limited by its current rating, I_r. However, the usual current rating for copper wire doesn't apply to inductors. Ratings based on a current density of 1000 circular mils/A—the loading that causes a 2% voltage drop per 100 ft of standard house wiring—aren't realistic.

Instead current ratings for industrial and military inductors are based on a more practical consideration —maximum temperature rise. Since these ratings range typically from 5 to 20% of the wire's fusing current, rating the inductor wire at 10% of its fusing current is realistic, not to mention convenient for calculation. This rating applies at T_m.

At 20 C, the fusing current for bare-copper magnet wire of diameter d_o is found by

Table 2. Magnet Wire Design Data.

AWG Size	Bare Wire				Single Film					Double Film				
	Max OD	Max I	Max Tensile Strength	Ω/ft	Max OD	ft/lb	Ω/lb	Tpi	Tpi^2	Max OD	ft/lb	Ω/lb	T_{pi}	T_{pi}^2
10	0.1024	33.6	82.4	0.00100	0.1047	31.6	0.0316	9.551	91.22	0.1061	31.5	0.0315	9.425	88.83
11	0.0912	28.2	65.3	0.00126	0.0935	39.8	0.0501	10.70	114.4	0.0948	39.7	0.0500	10.55	111.3
12	0.0812	23.7	51.8	0.00159	0.0834	50.3	0.0800	11.99	143.8	0.0847	50.0	0.0795	11.81	139.4
13	0.0724	19.9	41.2	0.00200	0.0746	63.3	0.1266	13.40	179.7	0.0757	62.9	0.1258	13.21	174.5
14	0.0644	16.7	32.6	0.00252	0.0666	79.9	0.2013	15.02	225.5	0.0682	79.3	0.1998	14.66	215.0
15	0.0574	14.1	25.9	0.00318	0.0594	101	0.3212	16.84	283.4	0.0609	100	0.3180	16.42	269.6
16	0.0511	11.8	20.5	0.00402	0.0531	127	0.5105	18.83	354.7	0.0545	126	0.5065	18.35	336.7
17	0.0455	9.94	16.3	0.00505	0.0475	159	0.8029	21.05	443.2	0.0488	158	0.7979	20.49	419.9
18	0.0405	8.35	12.9	0.00639	0.0424	201	1.284	23.58	556.2	0.0437	199	1.272	22.88	523.6
19	0.0361	7.02	10.2	0.00805	0.0379	253	2.037	26.39	696.2	0.0391	251	2.020	25.58	654.1
20	0.0322	5.92	8.14	0.0101	0.0339	318	3.212	29.50	870.2	0.0351	315	3.182	28.49	811.7
21	0.0286	4.95	6.42	0.0128	0.0303	402	5.146	33.00	1089	0.0314	397	5.082	31.85	1014
22	0.0254	4.15	5.07	0.0162	0.0270	508	8.230	37.04	1372	0.0281	503	8.149	35.59	1266
23	0.0227	3.50	4.05	0.0203	0.0243	633	12.85	41.15	1694	0.0253	625	12.69	39.53	1562
24	0.0202	2.94	3.20	0.0257	0.0217	806	20.71	46.08	2124	0.0227	794	20.41	44.05	1941
25	0.0180	2.47	2.54	0.0324	0.0194	1013	32.82	51.55	2657	0.0203	990	32.08	49.26	2427
26	0.0160	2.07	2.01	0.0410	0.0173	1282	52.56	57.80	3341	0.0182	1260	51.66	54.95	3019
27	0.0143	1.75	1.61	0.0514	0.0156	1608	82.65	64.10	4109	0.0164	1580	81.21	60.98	3718
28	0.0127	1.47	1.27	0.0653	0.0140	2033	132.8	71.43	5102	0.0147	1990	129.9	68.03	4628
29	0.0114	1.25	1.02	0.0812	0.0126	2525	205.0	79.37	6299	0.0133	2470	200.6	75.19	5653
30	0.0101	1.04	0.801	0.104	0.0112	3215	334.4	89.29	7972	0.0119	3140	326.6	84.03	7062
31	0.0090	0.874	0.636	0.131	0.0100	4065	532.5	100.0	10000	0.0108	3950	517.4	92.59	8573
32	0.0081	0.747	0.515	0.162	0.0091	5000	810.0	109.9	12076	0.0098	4880	790.6	102.0	10412
33	0.0072	0.626	0.407	0.206	0.0081	6369	1312	123.5	15242	0.0088	6170	1271	113.6	12913
34	0.0064	0.524	0.322	0.261	0.0072	8064	2105	138.9	19290	0.0078	7870	2054	128.2	16437
35	0.0057	0.441	0.255	0.331	0.0064	10210	3380	156.2	24414	0.0070	9940	3290	142.9	20408
36	0.0051	0.373	0.204	0.415	0.0058	12760	5295	172.4	29727	0.0063	12440	5163	158.7	25195
37	0.0046	0.319	0.166	0.512	0.0052	15800	8090	192.3	36982	0.0057	15300	7834	175.4	30779
38	0.0041	0.269	0.132	0.648	0.0047	19920	12908	212.8	45269	0.0051	19300	12506	196.1	38447
39	0.0036	0.221	0.101	0.847	0.0041	26040	22056	243.9	59488	0.0045	25100	21260	222.2	49383
40	0.0032	0.185	0.0804	1.08	0.0037	33110	35759	270.3	73046	0.0040	32200	34776	250.0	62500
41	0.0029	0.160	0.0661	1.32	0.0033	40100	52932	303.0	91827	0.0036	39500	52140	277.8	77160
42	0.0026	0.136	0.0531	1.66	0.0030	51000	84660	333.3	111111	0.0032	49800	82668	312.5	97656
43	0.023	0.113	0.0475	2.14	0.0026	65800	140.8k	384.6	147928	0.0029	63700	136.3k	344.8	118906
44	0.0021	0.0985	0.0346	2.59	0.0024	79400	205.6k	416.7	173611	0.0027	76300	197.6k	370.4	137174
45	0.00176	0.0756	0.0243	3.62	0.00205	104k	376.5k	487.8	237954	0.00230	99600	360.6k	434.8	189036
46	0.00157	0.0637	0.0194	4.54	0.00185	132k	599.3k	540.5	292184	0.00210	126k	572.0k	476.2	226757
47	0.00140	0.0536	0.0154	5.71	0.00170	162k	925.0k	588.2	346020	0.00190	153k	873.6k	526.3	277003
48	0.00124	0.0447	0.0121	7.29	0.00150	205k	1.494M	666.6	444444	0.00170	199k	1.451M	588.2	346020
49	0.00111	0.0379	0.0097	9.09	0.00130	258k	2.345M	769.2	591716	0.00150	252k	2.291M	666.6	444444
50	0.00099	0.0319	0.0077	11.4	0.00120	312k	3.557M	833.3	694444	0.00140	306k	3.488M	714.3	510204
51	0.00088	0.0267	0.0061	14.5	0.00110	416k	6.032M	909.1	826446					
52	0.00078	0.0223	0.0048	18.4	0.00100	555k	10.21M	1000	1.000M					
53	0.00070	0.0190	0.0038	22.9	0.00085	667k	15.27M	1176	1.384M					
54	0.00062	0.0158	0.0030	29.1	0.00075	859k	25.00M	1333	1.777M					
55	0.00055	0.0132	0.0024	37.0	0.00070	1.090M	40.33M	1429	2.041M					
56	0.00049	0.0111	0.0019	46.6	0.00065	1.380M	64.31M	1538	2.367M					
Units	Inches	Amperes	Pounds	Ω/ft	Inches	ft/lb	Ω/lb	T_{pi}	T_{pi}^2	Inches	ft/lb	Ω/lb	Tpi	Tpi^2

Maximum ODs. Ω/ft and ft/lb are taken from Materials and Processes Handbook. Maximum rated current is 10% of the fusing current at 20 C. Maximum tension is based upon a tensile strength of 10,00 PSI. Ω/lb is derived from (Ω/ft) x (ft/lb). Tpi = 1/Max OD. Tpi^2 = $(1/\text{Max OD})^2$

$$I_f = 10{,}244\ d_o^3 \quad (12)$$

As a result, the current rating at 20 C is

$$I_{ro} = 0.1\ I_f, \quad (13)$$

Furthermore, for a required I_r, the magnet wire's minimum current rating at 20 C must be

$$I_{ro} = I_r\ [1 + 0.00393\ (T_m - 20)] \quad (14)$$

Current ratings for copper magnet wire, based on Eq. 13, are tabulated in Table 2 along with other selected magnet-wire design data.

Finding the effective volume

Using your values for B and H, determine the minimum effective volume, V_{em}, that will sustain your inductor's operating conditions.

$$V_{em} = 0.4\pi \times 10^8\ L_m I_m^2/(B\ H). \quad (15)$$

For ungapped cores like toroids, the actual core volume must equal or exceed V_{em}. But meeting this requirement may make the core size excessive. Fortunately, however, an air gap in the magnetic circuit can reduce core size significantly. If the air-gap length, l_g, is small with respect to the effective magnetic-path length, l_e, the equivalent effective volume, V_e, is:

$$\begin{aligned} V_e &= A_c l_e \\ &= A_c\ (l_c + U_i\ l_g) \\ &= V_c + (A_c\ U_i\ l_g), \end{aligned} \quad (16)$$

where l_e is the magnetic path length of the core, A_c is the core's cross-sectional area and V_c is the actual volume.

To get the L_m when you select the core gap ensure

$$V_e \geq V_{em}. \quad (17)$$

Armed with the minimum effective core volume, select the smallest core that can sustain the required inductance. With the help of core-size indexes pick a core from magnetic-core catalogs. They also provide data for the winding area, W_a, and for A_c that you can use in

$$W_a A_c = 5.067 \times 10^8\ L_m I_m d_i^2/(k\ B). \quad (18)$$

Here d_i is the diameter of the insulated-wire (double-film insulation is recommended), and k is the winding-utilization, or "fit," factor. For toroidal windings, k is typically 0.4; for bobbin windings, 0.8.

The core must satisfy Eqs. 15 and 18. Often, the core's geometry is severely limited by mounting space and dc winding resistance, R_{dc}. (Other factors that affect core geometry are compared in Table 3.)

Even slug-type inductors can be designed with this step-by-step procedure, but you must empirically determine l_g and V_e for slugs.

Now that you know the material, size and geometry of the core, you can calculate the maximum value of the incremental inductance index, A_{Lm}, from

$$A_{Lm} = (B\ A_c)^2 \times 10^{-16}/(L_m I_m^2). \quad (19)$$

Then with A_{Lm}, compute the number of turns, N, required for the L_m you need:

$$N = \sqrt{L_m/A_{Lm}} \quad (20)$$

Take N and H, and determine l_e:

$$l_e = 0.4\pi N I_m/H. \quad (21)$$

For cores without air gaps, such as toroids, make sure that

Table 3. Core-geometry selection criteria.

Selection Factor	E-U-I Cores	Pot Cores	Toroid Cores	Slug Cores	Other Shielded Cores
Core Cost	Low	High	Low	Low	High
Winding Cost	Low	Low	High	Low	Low
Winding Flexibility	Excellent	Fair	Good	Good	Fair
Mounting Flexibility	Good	Good	Fair	Fair	Good
Shielding	Fair	Excellent	Good	Poor	Good

$$l_c \geq l_e. \quad (22)$$

For cores with air gaps, compute the air-gap length from

$$l_g = (l_e - l_c)/U_i. \quad (23)$$

Now you can find the effective permeability:

$$U_e = U_i/[1 + (U_i l_g/l_c)]. \quad (24)$$

For core geometries in which an air gap interrupts the magnetic circuit twice, the inserted material thickness should be half that computed in Eq. 23.

The air gap affects the initial-inductance index, A_{Lo}, as follows:

$$A_{Lo} = 0.4\pi \times 10^{-8}\ A_c/[(l_c/U_i) + l_g]. \quad (25)$$

Calculate the initial inductance, L_o, from

$$L_o = A_{Lo}\ N^2. \quad (26)$$

Next, compute the percent change in inductance L

$$\%L = [(L_m/L_o) - 1]\ 100. \quad (27)$$

Don't let the inductance change more than 25%. Next, compute P_t, the total power dissipated by the complete inductor—both the winding and the core. First determine the power dissipated in the windings, P_w.

The d_i used for the magnet wire when finding the minimum-sized core is the minimum for the I_r. However, the W_a of the actual core may be able to accept a wire with a large diameter and thereby lower the windings' power loss. The maximum diameter for the insulated wire is related to the winding density in turns per inch, tpi^2, by

$$d_i = \sqrt{1/tpi^2}. \quad (28)$$

The winding density must conform to

$$tpi^2 = 6.452\ N/(k\ W_a). \quad (29)$$

Select a wire with the best size for lowest dc resistance per unit length, p. The dc winding resistance, for a particular mean length per turn, l_{tm}, is found with

$$R_{dc} = N\ l_{tm}\ p. \quad (30)$$

Compute P_w, using R_{dc}, the reference temperature T_o, the wire's thermal coefficient of resistance (r), and the T_m and I_r:

$$P_w = I_r^2 R_{dc}\ [1 + r\ (T_m - T_o)]. \quad (31)$$

If T_o is 20 C, r is 0.00393; if T_o is 25 C, r is 0.00385.

Now, determine the core loss, P_c, from the data for

core loss per unit volume, C_v, which most core manufacturers either graph or tabulate. If necessary, you can extrapolate the value of C_v for your conditions:

$$P_c = C_v V_c. \quad (32)$$

Finally, the total power dissipated by the inductor

$$P_t = P_w + P_c. \quad (33)$$

Of course, since you haven't built your inductor yet you can only estimate its maximum operating temperature. Surface dissipation, S_d, is the wide-ranging variable that makes determining the T_m fuzzy. The many material variations plus nonuniformity in construction and processing can significantly alter S_d. But, you can at least calculate a value for S_d that is close enough for a first-order estimate.

Find S_d at the ambient temperature, T_a, by

$$S_d = 0.0014 + 1.217 \times 10^{-6} T_a^{1.585}. \quad (34)$$

With the total surface area, A_s, and S_d, approximate thermal conductance:

$$G_t = A_s S_d, \quad (35)$$

Then the temperature rise:

$$T_r = P_t/G_t, \quad (36)$$

and finally the crucial variable, T_m:

$$T_m = T_a + T_r. \quad (37)$$

If you find the T_m gets too high, reduce it by increasing A_s, R_{dc}, or both.

Putting the steps all together

To see how all the equations work together, consider an inductor meeting the following requirements:

- L_o = 5.6 mH at 0-Adc.
- L_m = 4.7 mH minimum at 1.4-A pk and 20 kHz with a 34% duty cycle.
- T_r = 60 C maximum at 20 C ambient, therefore T_m = 80 C.
- I_{dc} = 0.
- The inductor must be mountable on a PC board and shielded.
- The inductor must be small.

Step 1: Determine the total current. Because I_{dc} is zero, from Eq. 1,

$$I_m = 1.4 + 0 = 1.4 \text{ A}$$

For a 34% duty cycle at 20 kHz,

$$t_{pr} = 1/20 \times 10^3 = 5 \times 10^{-5} \text{ s},$$

and

$$P_d = 0.34 \times 5 \times 10^{-5} = 1.7 \times 10^{-5} \text{ s}.$$

Assuming that I_c is 10% of I_m,

$$I_c = 0.1 \times 1.4 = 0.14 \text{ A}.$$

Although not specified in this design, E_{pk} is always of interest, so from Eq. 5,

$$E_{pk} = (1.4 - 0.14)\, 4.7 \times 10^{-3}/(1.7 \times 10^{-5}) = 348 \text{ V pk}.$$

From Eq. 6,

$$I_{eff} = \sqrt{\frac{1.7 \times 10^{-5} [1.4^2 + (1.4 \times 0.14) + 0.14^2]}{3 \times 5 \times 10^{-5}}} = 0.497 \text{ A}.$$

And from Eq. 2,

$$I_r = 0.497 + 0 = 0.497 \text{ A}.$$

Step 2: Select the core material. Choose F2000 ferrite for the core material because, as you can see from Table 1, it has the greatest operating flux density. From the table,

$$B_s = 4400 \text{ G}.$$
$$B_r = 1500 \text{ G}.$$

And from Table 2,

$$U_i = 2000 \text{ G}.$$
$$T_m = +125 \text{ C}.$$

From the supplier's data, at 2900 G and 20 kHz,

$$C_{vf} = 12 \ \mu\text{W/cm}^3/\text{Hz}.$$

Therefore, from Eq. 7,

$$C_v = 12 \times 10^{-6} \times 20 \times 10^3 = 0.24 \text{ W/cm}^3$$

Step 3: Determine the optimum B and H. From Eq. 9,

$$B = 4400 - 1500 = 2900 \text{ G}.$$

From Eq. 10,

$$U_m = 2000 \times 4.7 \times 10^{-3}/5.6 \times 10^{-3} = 1679 \text{ G/Oe}.$$

From Eq. 11,

$$H = 2900/1679 = 1.73 \text{ Oe}.$$

Step 4: Select the minimum-sized magnet wire. With an 80-C value for T_m in Eq. 14,

$$I_{ro} = 0.497 [1 + 0.00393 (80 - 20)] = 0.614 \text{ A}.$$

From the data in Table 3, the thinnest wire that can accommodate I_{ro} is AWG 33, whose

$$p = 0.206 \ \Omega/\text{ft},$$

and

$$d_i = 0.0088 \text{ in}.$$

Step 5: Determine the minimum effective volume. From Eq. 15,

$$V_{em} = 0.4\pi \times 10^8 \times 4.7 \times 10^{-3} \times 1.4^2/(2900 \times 1.73) = 231 \text{ cm}^3.$$

To provide this effective volume, an upgapped core would have to fill a 6.13-cm cube—much too large for mounting on a PC board. Use a gapped core instead; and since shielding is required, make it a pot core.

Step 6: Select the minimum-sized core. From Eq. 18,

$$W_a A_c = \frac{5.067 \times 10^8 \times 4.7 \times 10^{-3} \times 1.4 \times 0.0088^2}{0.8 \times 2900} = 0.1113 \text{ cm}^4.$$

A search through core catalogs reveals the smallest standard pot core that you can use is 22 × 13 mm. For this core

$$A_c = 0.63 \text{ cm}^2$$

and

$$W_a = 0.292 \text{ cm}^2.$$

Therefore,

$$W_a A_c = 0.292 \times 0.63 = 0.1840 \text{ cm}^4,$$

which is, of course, large enough. From the catalogs, you get the following additional core data:

$$l_c = 3.15 \text{ cm.}$$
$$V_c = 2 \text{ cm.}$$
$$A_s = 18.02 \text{ cm}^2.$$
$$W_o = 0.0453 \text{ in.}$$
$$l_{tm} = 0.145 \text{ ft.}$$

Step 7: Determine the number of turns. From Eq. 19,

$$A_{Lm} = (2900 \times 0.63)^2 \times 10^{-16}/(4.7 \times 10^{-3} \times 1.4^2)$$
$$= 3.623 \times 10^{-8} \text{ H/turns}^2.$$

Then from Eq. 20

$$N = \sqrt{4.7 \times 10^{-3}/(3.623 \times 10^{-8})}$$
$$= 360 \text{ turns}$$

Step 8: Determine the air gap size. From Eq. 21,

$$l_e = 0.4\pi \times 360 \times 1.4/1.73$$
$$= 366 \text{ cm}$$

Then, from Eq. 23,

$$l_g = (366 - 3.15)/2000$$
$$= 0.182 \text{ cm}$$
$$= 0.072 \text{ in.}$$

The air gap interrupts the magnetic circuit twice, so the spacer should be 0.036 in. thick—half the computed value of l_g.

Check V_e in Eq. 16:

$$V_e = 2 + (0.63 \times 2000 \times 0.182)$$
$$= 231 \text{ cm}^3.$$

Therefore, V_e complies with the V_{em} required by Eq. 17.

Step 9: Determine the incremental effect. From Eq. 25,

$$A_{LO} = 0.4\pi \times 10^{-8} \times 0.63 / [(3.15/2000) + 0.182]$$
$$= 4.31 \times 10^{-8} \text{ H/turn.}$$

Then, from Eq. 26,

$$L_o = 4.31 \times 10^{-8} \times 360^2$$
$$= 5.59 \text{ mH,}$$

which is close enough to the required 5.6 mH. If L_o isn't close enough, change the turns ratio appropriately—a simple process using Eq. 26.

Step 10: Determine the total power loss. From Eq. 29,

$$\text{tpi}^2 = 360/(0.8 \times 0.0453)$$
$$= 9934 \text{ turns/in.}^2$$

From the wire data in Table 2, you can use AWG 32 heavy-film wire instead of AWG 33. Then,

$$p = 0.162 \ \Omega\text{/ft.}$$

From Eq. 30,

$$R_{dc} = 360 \times 0.145 \times 0.162$$
$$= 8.46.$$

From Eq. 31,

$$P_w = 0.497^2 \times 8.46 [1 + 0.00393 (80 - 20)]$$
$$= 2.54 \text{ W.}$$

From Eq. 32,

$$P_c = 0.24 \times 2$$
$$= 0.48 \text{ W.}$$

Note that the core loss is much smaller than the winding loss. From Eq. 33,

$$P_t = 0.48 + 2.54$$
$$= 3.02 \text{ W.}$$

Step 11: Determine the maximum temperature. From Eq. 34,

$$S_d = 0.0014 + 1.2717 \times 10^{-6} \times 25^{1.585}$$
$$= 0.0016 \text{ W/cm}^2/°\text{C.}$$

From Eq. 35,

$$G_t = 0.0016 \times 18.02$$
$$= 0.02883 \text{ W/°C.}$$

From Eq. 36,

$$T_r = 3.02/0.02883$$
$$= 105 \text{ C.}$$

From Eq. 37,

$$T_m = 20 + 105$$
$$= 125 \text{ C.}$$

This value of T_m is too high. The open construction of the proposed inductor doesn't have enough surface to limit T_r to 60 C max. From Eq. 36, the minimum thermal conductance required is

$$G_t = 3.02/60$$
$$= 0.0503 \text{ W/°C}$$

Therefore, from Eq. 35, the minimum A_s required is

$$A_s = 0.0503/0.0016$$
$$= 31.43 \text{ cm}^2.$$

The maximum diameter and height of the pot core are 0.866 inches and 0.536 inches, respectively. So you should be able to encapsulate it, with thermally conductive epoxy, in a round or rectangular plastic shell. The nearest suitably sized round shell has an outside diameter of 1.187 inches, a height of 0.75 inches, and a thickness of 0.03 inches. Therefore,

$$A_s = 5.01 \text{ in.}^2$$
$$= 32.32 \text{ cm}^2.$$

Combining Eqs. 35, 36 and 37,

$$T_m = 20 + 3.02/0.0016 \times 32.32$$
$$= 20 + 58$$
$$= 78 \text{ C,}$$

which meets the required design goal. ■■

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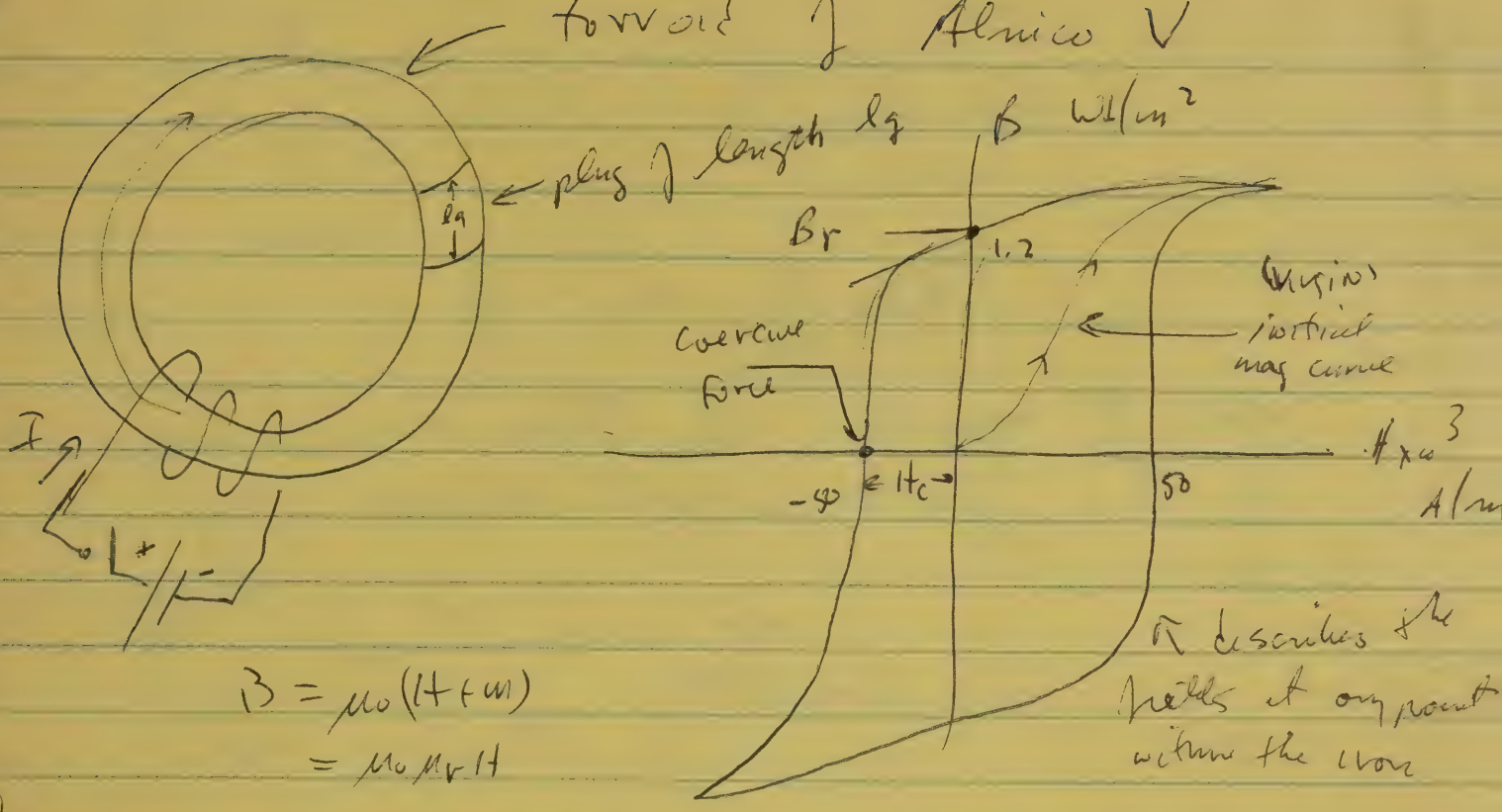


$B = \mu_0(H + M)$

$= \mu_0 \mu_r H$

↑ describes the fields at any point within the iron

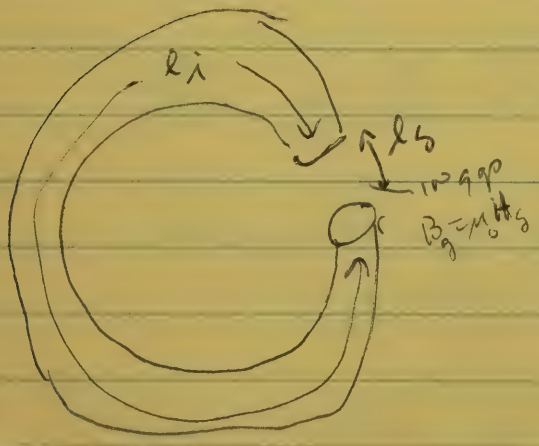
magnetize with I through coil

remove I and B remains at ≈ 1.2 Wb/m² = B_r

remanent magnetization, remanance, retentivity

Now remove plug (want 2nd eq of B_i vs H_i

what happens?



$$\oint H \cdot dl = NI = 0$$

$$H_i l_i + H_g l_g = 0$$

boundary condition $B_i = B_g$ (no fringing assumption, small gap)

i.e. normal B is continuous

$$H_i = -H_g \frac{l_g}{l_i} = -\frac{B_g}{\mu_0}\frac{l_g}{l_i}$$

Since $B_g = \mu_0 H_g$ in gap

, 1975.

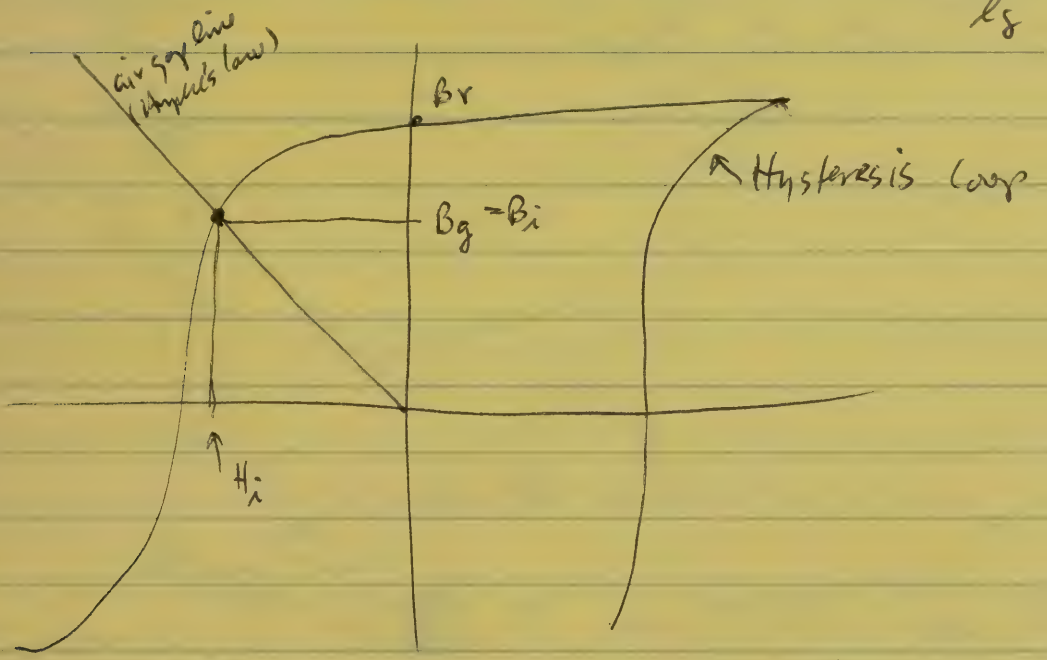
ember 20, 1977

Finally $H_i = -\frac{B_i}{\mu_0}\frac{l_g}{l_i}$

and

$$B_i = -\frac{l_i}{l_g}\mu_0 H_i$$

this is a straight line through the origin with negative slope $-\mu_0 \frac{l_i}{l_g}$



Flux in gap now is given as $\phi_g = B_g A_{area}$

Note: as l_g is increased, flux decreases and $B_g \downarrow$

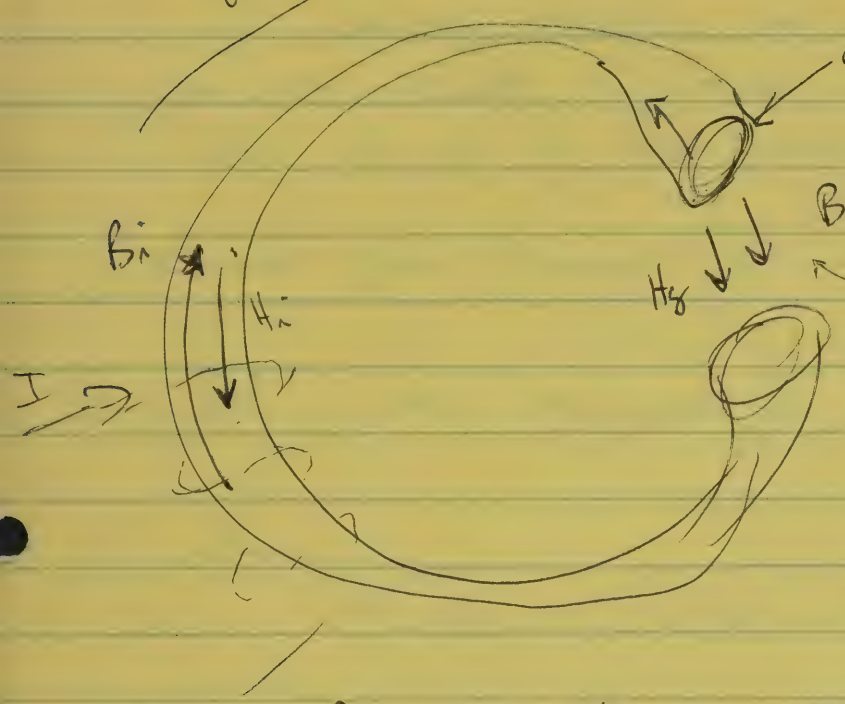
Note: H_i is determined in the iron & it is oppositely directed to B_i

Since $B = \mu H = \mu_0 (H + M)$

so $B_i = \mu_0 (H_i + M)$

$$M = \frac{B_i}{\mu_0} - H_i$$

M terminates on "mag charge"



$$B = \mu_0 H + \mu_0 M$$

We must choose

$$\nabla \cdot B = 0 = \mu_0 \nabla \cdot H + \mu_0 \nabla \cdot M$$

$$\nabla \cdot M = -\nabla \cdot H = \rho_m$$

$\nabla \cdot D = \rho$

demagnetizing field H_i can cause spontaneous demagnetization so a keeper should be used — this removes poles — discontinuity in divergence of H and H_i goes to zero as B_i goes to B_r — i.e. make μ of gap $\mu \to \infty$ vacuum μ_0 then air gap line goes nearly vertical and $H_i \to 0$

Quality criterion

at a given operating point one has a BH product and BH has dimensions of energy density i.e. Joules/m³
so one expects at max energy density the design is the most economical

Consider from Ampere's Law $H_i l_i + H_g l_g = 0$

and from Maxwell's eq $\phi_{gap} = \phi_{iron}$

$B_g A_g = B_i A_i$

then

$Vol_{iron} = l_i A_i$

$= -\frac{H_g l_g}{H_i} \frac{B_g A_g}{B_i}$ ($B = \mu H$)

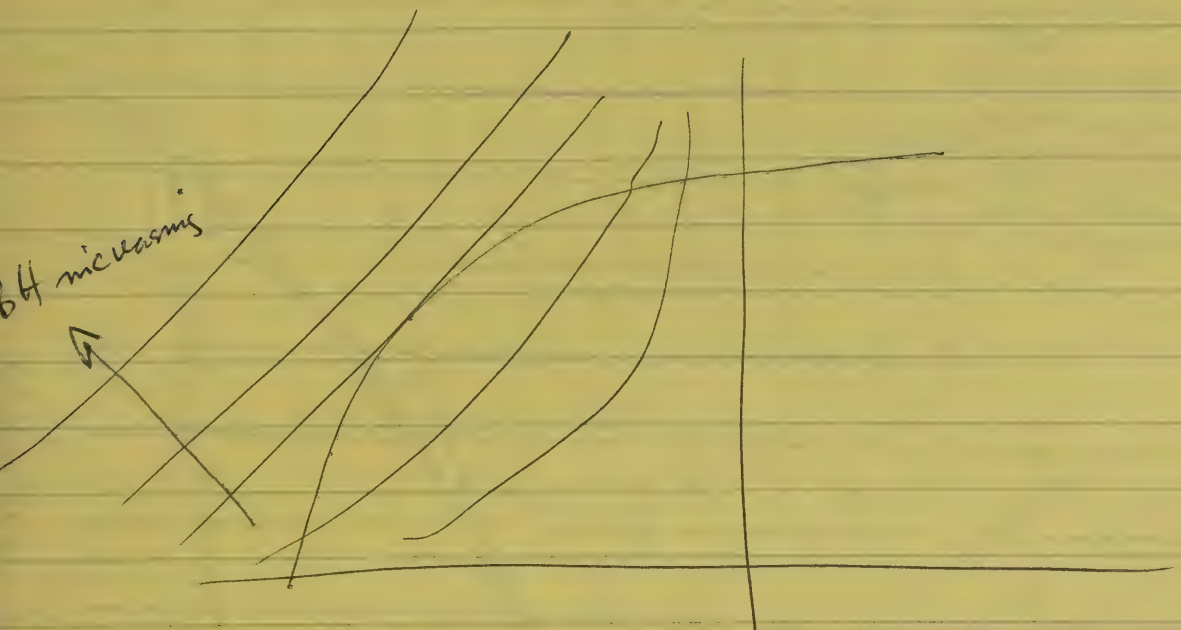
$= \frac{B_g^2 l_g A_g}{\mu_0 [-B_i H_i]}$ (Note $H_i < 0$)

$\Rightarrow B_i H_i > 0$

thus when B in gap is specified as a design criterion and Vol_{gap} is specified in a design then Vol_{iron} is minimized when $B_i H_i$ is maximized

to be expected since this is max magnetic energy density

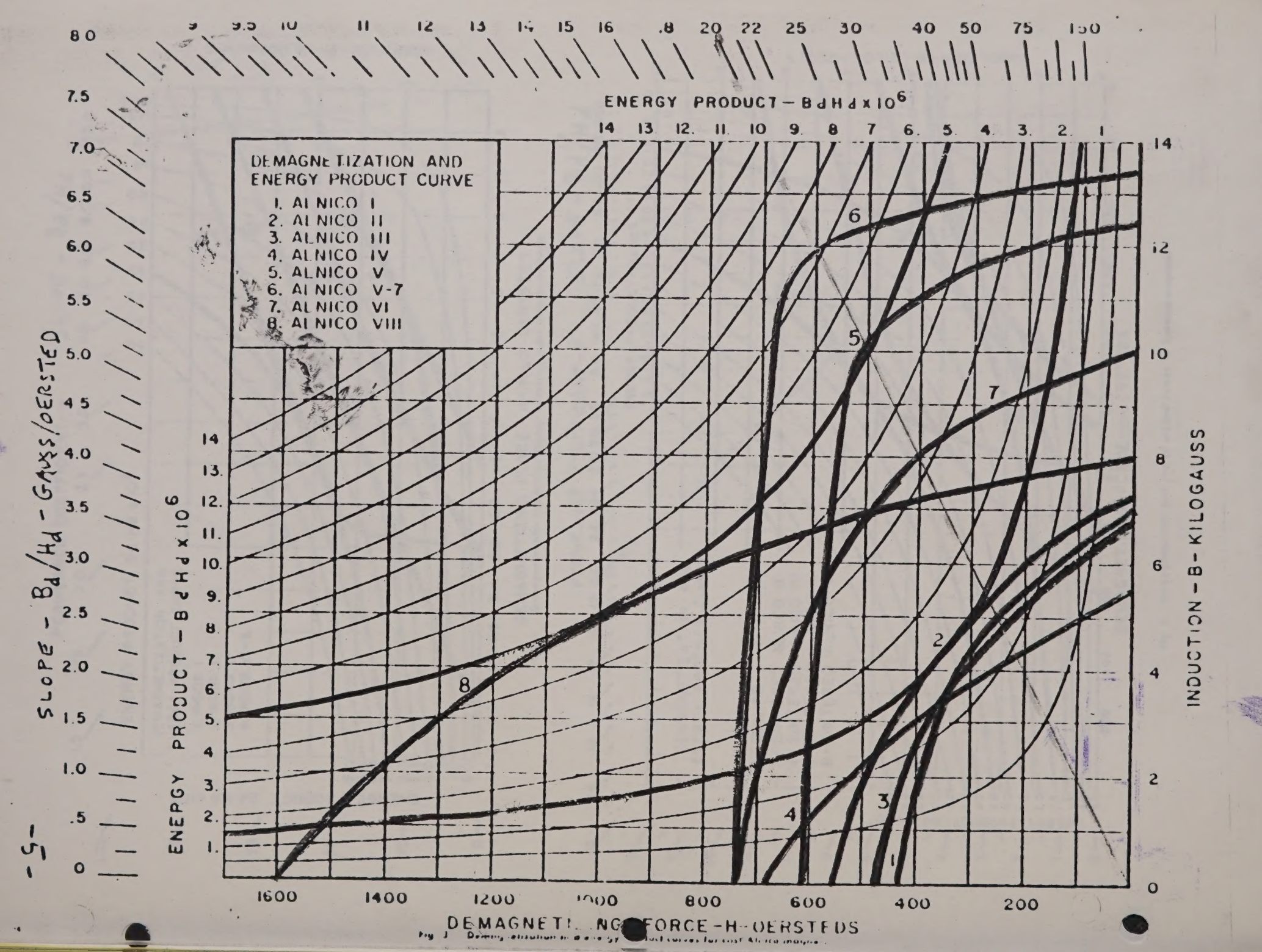
B H product = const defines a series of hyperbolas

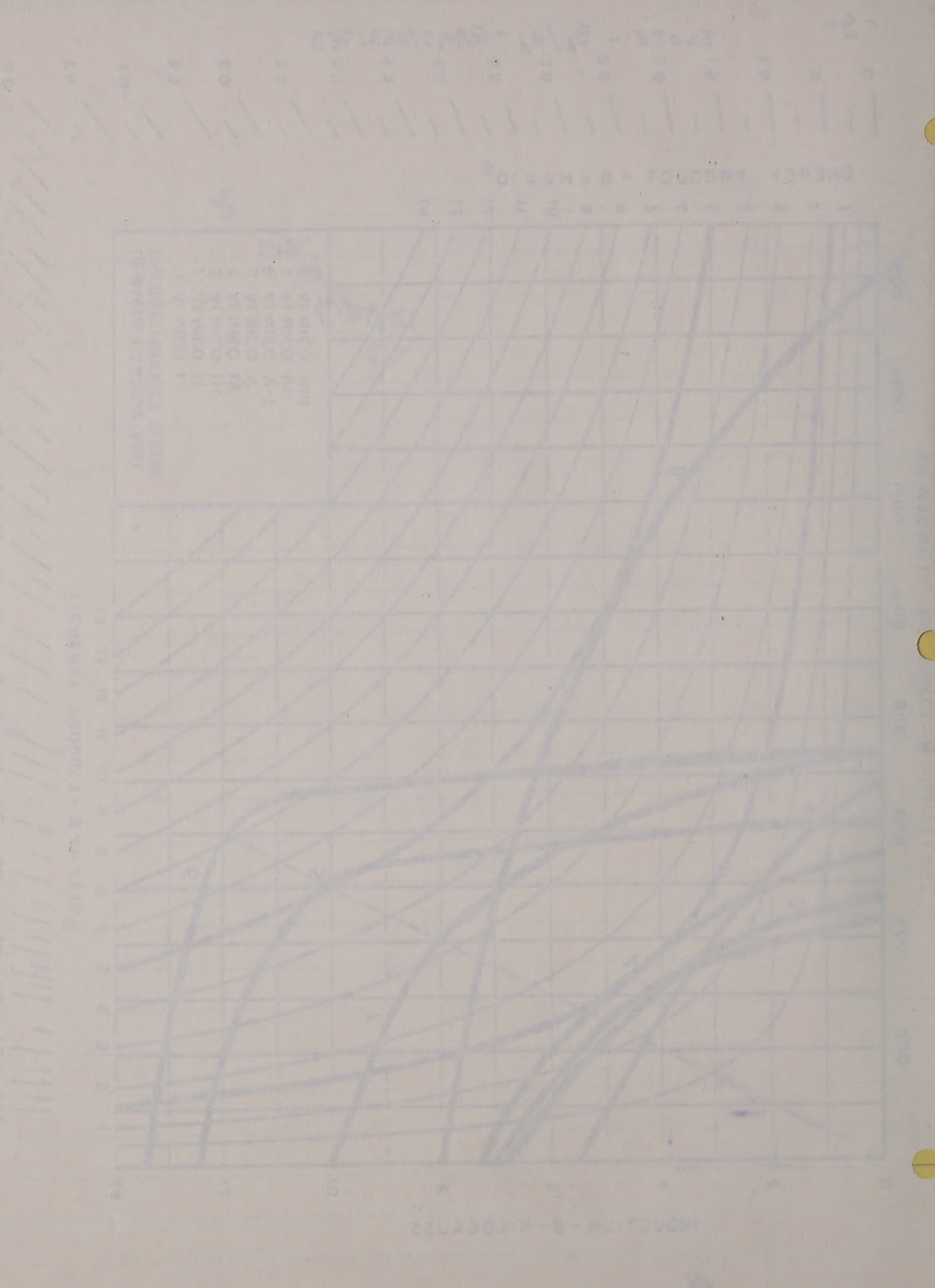


Wherever BH = const is tangent to the mag curve will be the point of max BH product and hence the minimum mass volume

1 Oersted = $4\pi \times 10^{-3}$ A/m

1 Gauss = 10^{-4} Tesla (Wb/m^2)


DEMAGNETIZATION AND ENERGY PRODUCT CURVE
1. ALNICO I
2. ALNICO II
3. ALNICO III
4. ALNICO IV
5. ALNICO V
6. ALNICO V-7
7. ALNICO VI
8. ALNICO VIII
ENERGY PRODUCT – $B_d H_d \times 10^6$
ENEPGY PRODUCT – $B_d H_d \times 10^6$
DEMAGNETIZING FORCE – H – OERSTEDS
INDUCTION – B – KILOGAUSS
SLOPE – B_d/H_d – GAUSS/OERSTED
-5-



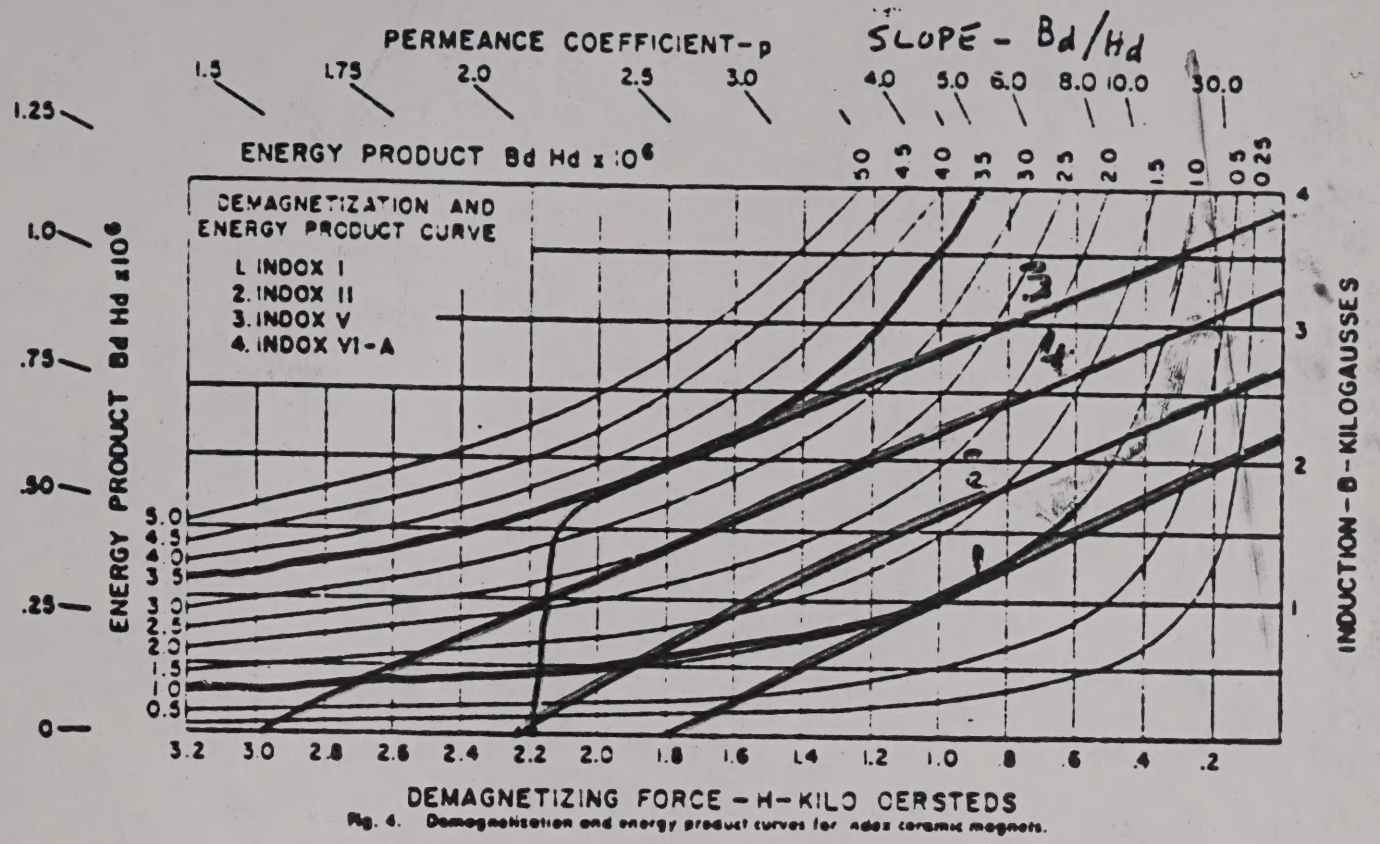


Fig. 4. Demagnetization and energy product curves for Indox ceramic magnets.

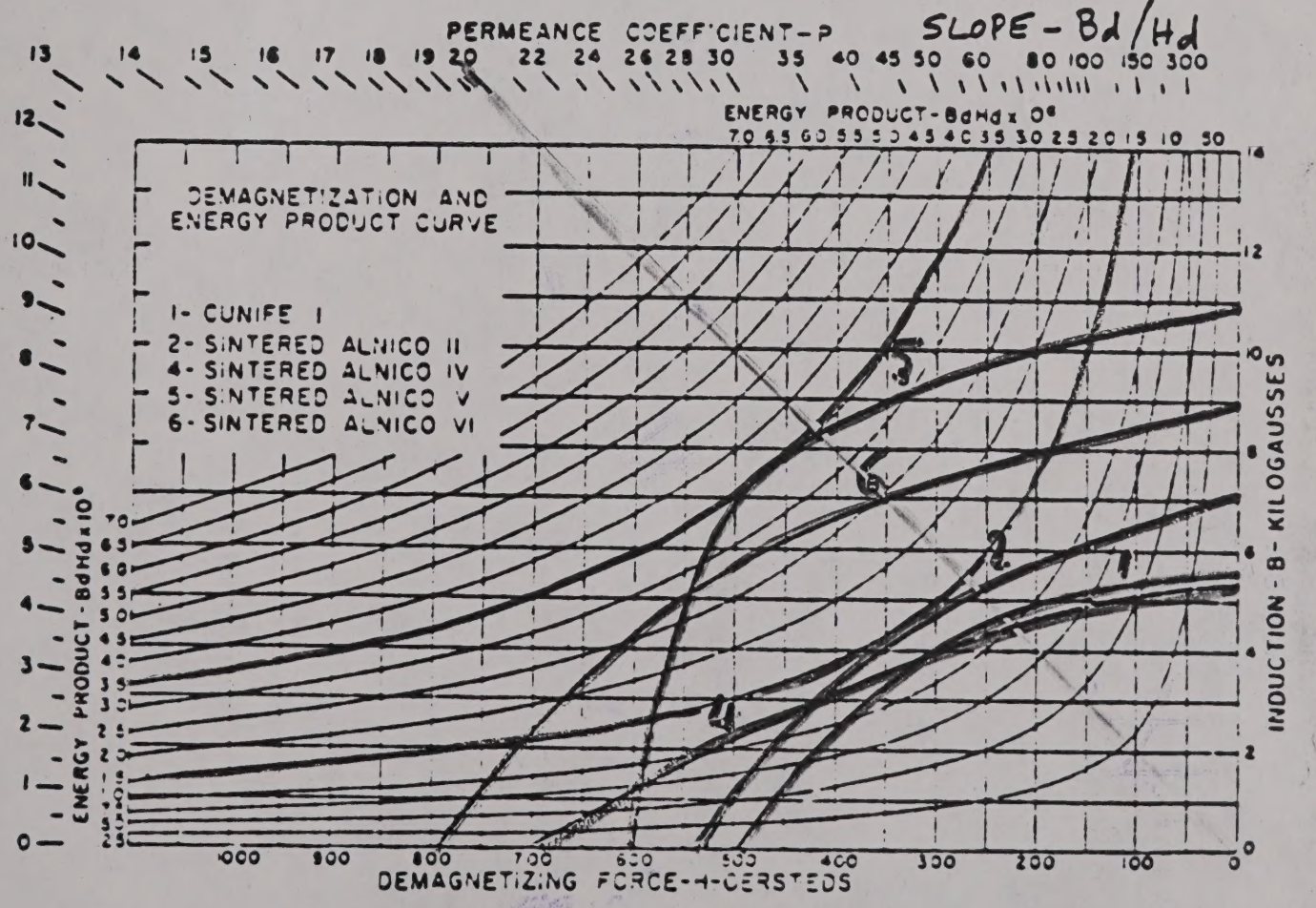


Fig. 5. Demagnetization and energy product curves for Sintered magnets.